NOTICE

Final Report

Project Title: Development of 50 kW Fuel Processor for Stationary Fuel Cell Applications

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Recipient: Chevron Technology Ventures LLC (Formerly Texaco Energy Systems, LLC)

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Award Number: DE-FC36- 03GO13102

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Cost-Sharing Partners: ChevronTexaco Technology Ventures LLC

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Project Objective: Chevron Technology Ventures LLC (CTV), formerly Texaco Energy Systems LLC (TES) and Cabot Superior MicroPowders (CSMP) will develop and test a fuel processor capable of producing a high hydrogen concentration (>98%) reformate, containing inconsequential levels of carbon dioxide and carbon monoxide. This will be done without the high capital and operating costs associated with pressure swing absorption (PSA) or membrane separation. The proposal team members will develop high durability CO_2 absorbents containing both high temperature water-gas shift (WGS) and steam reforming catalysts. Process design, system efficiency, and cost estimate studies will be performed, leading to the design, construction, and testing of a “stand alone,” low cost, natural gas fed 50 kW fuel processor.

Background: The fuel processor is one of the major influences on the performance, durability, cost and size/weight of a PEM fuel cell system. A low cost method to produce high purity hydrogen from natural gas will have an enormous impact. Conventional methods of natural gas reforming for this application such as steam methane reforming (SMR) and autothermal reforming (ATR), lead to relatively low hydrogen content gas streams. The fuel feeds are highly contaminated by CO and CO_2 and require extensive purification prior to delivery to a fuel cell system. Elimination of the purification plant would be an enormous improvement in both CAPEX and OPEX. This can be achieved by an absorption enhanced reformer (AER) that combines steam methane reforming, water-gas shift, and CO_2 absorption in one reactor to produce a synthesis gas with relatively high hydrogen purity and low CO_2 and CO content. The potential benefits are well known and have been the subject of much study, but no materials capable of withstanding many thousands of reforming/regeneration cycles have been identified yet.

The technical goals of this project are to use the unique manufacturing capabilities of CSMP to create new, cost effective materials that combine carbon dioxide fixing, steam reforming, and water-gas shift catalytic properties. With the new material CTV will develop an efficient, low cost reformer capable of fueling a 50 kW PEM fuel cell.

EXECUTIVE SUMMARY

The objective of the project was to develop and test a fuel processor capable of producing high hydrogen concentration (>98%) with less than ppm quantities of carbon dioxide and carbon monoxide at lower capital cost and higher efficiency, compared to conventional natural gas reformers. It was intended that we achieve our objective by developing simple reactor/process design, and high durability CO2 absorbents, to replace pressure swing adsorption (PSA) or membrane separators.

The work on adsorbent development was focused on the development of calcium oxide-based reversible CO_2 absorbents with various microstructures and morphologies to determine the optimum microstructure for long-term reversible CO_2 absorption. The effect of powder production process variables was systematically studied including: the final target compositions, the reagents from which the final products were derived, the pore forming additives, the processing time and temperature. The sorbent materials were characterized in terms of their performance in the reversible reaction with CO_2 and correlation made to their microstructure.

Large scale spray processing equipment, powder post processing equipment, and mixer and extruder was installed and commissioned, for large scale production of the chosen sorbent material. Microreactor test stand was designed for testing powders and extrudates under steam reforming conditions. Results from microreactor tests were used for screening of sorbents and optimization of reforming and regeneration temperatures. Two 1 kW (2 Kg/day) reactors and test bays were designed for testing extrudates under practical regeneration and reforming conditions. 1 kW reactors were used for testing different regeneration methods including catalytic and flame combustion. A detailed thermodynamic steady state model as well as dynamic model was built using Aspen® to optimize operating conditions and predict system efficiency. Detailed engineering design was performed on the 50 kW fuel processor design to estimate efficiency and capital cost. Design package included detailed process & instrumentation diagram (P&ID), reactor design, heat exchanger specification, pressure drop estimation, material specification and parasitic power estimation.

In TGA, sorbent material retained significant capacity over many cycles indicating a step change in durability compared to commercially available materials. However, in practical regeneration conditions, the material capacity did not retain significant capacity for 500 cycles. The maximum regeneration temperature tolerated by the sorbent material dictated use of large air flow during regeneration and resulted in two issues: first, the heat loss in the system was significant mainly due to large regeneration flow rate and second, increased air flow requirement increased the pressure drop through the system and hence, required significant parasitic power for the air compressor. These two issues resulted in reduced thermal and net efficiency of the system. Heat integration scheme for maximum heat recovery required large air-to-air heat exchangers with small pinch temperatures. This led to large and expensive heat exchanger requirement for the system.

It was determined that the predicted thermal efficiency of the 50 kW system will not meet the thermal efficiency target of 75% for the go/no-go decision and hence, decision was made to close-out the project.

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Task 1: Materials Development and Characterization

The goal of the materials development effort performed by Cabot Superior MicroPowders (CSMP) was to develop high durability CO_2 absorbents containing both high temperature water-gas shift (WGS) and steam reforming catalysts. The materials approach relied on CSMP's spray conversion powder production platform enabling the production of materials with unique microstructure and composition, suitable for Absorption Enhanced Reforming (AER).

Two main types of materials were the focus of the development effort performed at CSMP: active and preferably relatively inexpensive reforming catalyst and a highly reactive, high capacity, highly reversible CO_2 absorbent. The major focus has been the development of a CO_2 absorbent that maintains a high capacity and controlled microstructure over a large number of cycles. The challenge in designing stable CO_2 absorbent materials comes from the fact that the product of the carbonation reaction, $CaCO_3$ has a much lower density than the reagent CaO. Therefore, for a fixed mass of CO_2 absorbent in a reactor bed, there is a large increase in volume as CaO is converted to $CaCO_3$. Due to the high temperature typically required for the sorbent decarbonation, particle sintering occurs leading to a significantly reduced CO_2 absorption capacity during the subsequent cycles. Highly active SMR catalysts are well known and the challenge in this context was how this material should be integrated into the AER scheme and to identify the optimum microstructure and transport distance between the site of the catalyst and the sorbent powder. CSMP utilized its spray-based powder manufacturing approach to develop and produce powders that have been specifically designed for AER using logical materials design concepts. A summary of the design aspects that were tested as part of the materials development work are described in Table 1 below. In each specific task, a design of experiments around the powder composition and spray processing conditions was performed and the properties of the powders were analyzed by physical characterization methods and Thermo Gravimetrical Analysis (TGA) for their CO_2 sorption capacity.

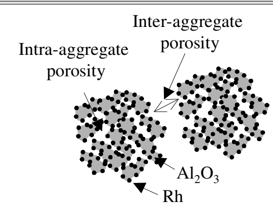
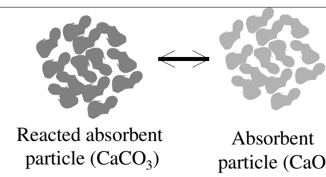
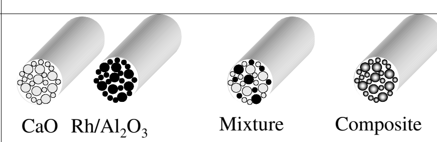
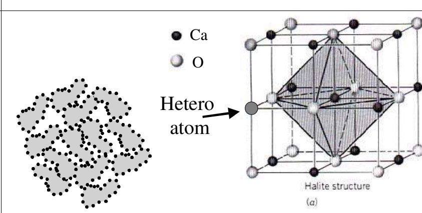
Issue/Function	**Material**	**Approach**	**Schematic**
Reforming catalyst	<0.5 wt.%Rh/Al_2O_3	High dispersion of Rh on Al_2O_3 with high Rh utilization in a microstructure that enables gas transport	
High capacity reversible CO_2 absorbent	Supported $CaCO_3$ e.g. $CaCO_3/Al_2O_3$ (95/5 wt.%)	Highly porous, high surface area $CaCO_3$ containing Al_2O_3 for structural integrity in pelletization "Regenerated" to form CaO in first step	
Combined reforming catalyst and CO_2 absorbent	<0.05wt.% $Rh/Al_2O_3/CaO$ composite	Systematic variation in proximity of catalysis and CO_2 adsorption: 1. Pelletized individual powders; 2. Pelletized mixed powders; 3. Composite powders	
Improved carbonation/ decarbonation kinetics	Supported $CaCO_3$ with additives or microstructura l enhancements	Two approaches: 1. Microstructural – introduce bond strain through nano-engineering 2. Chemical – introduce additives that alter bond strength and kinetics of the rate-determining step	

Table 1: Summary of materials and structures that were developed during the work program

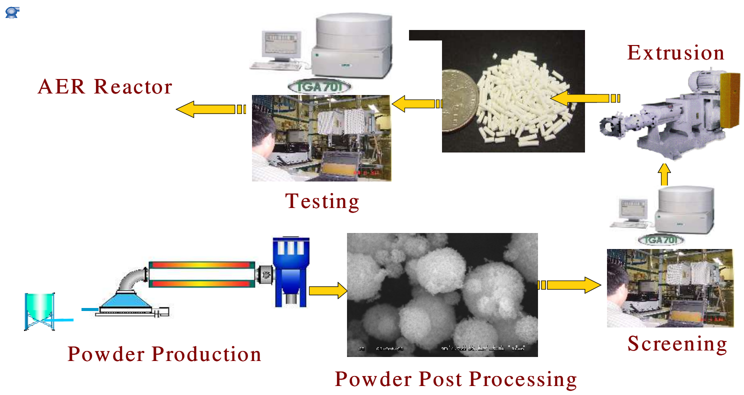


Figure 1: Materials synthesis approach and work flow

The testing of the materials in its final application (AER reactor) requires their formulation by a pelletization process into extrudates with the necessary crush strength and durability under cycling. Figure 1 represents the materials synthesis approach and workflow. It starts with powder synthesis at variable conditions, followed by post processing (or additional calcination) of the spray processed powders, testing and formation of extrudates, followed by evaluation of the extrudates by various methods at CSMP and in the AER reactor by TES.

Subtask 1.1: Steam Reforming Catalysts

A steam reforming catalyst is required to convert methane into CO and H_2. Nickel-based catalysts are often used because they are active and inexpensive, but they are more easily deactivated by sulfur poisoning and carbon deposition at steam to carbon ratios below 3. This can lead to shorter life and reliability of the reforming system. As a reliable alternative, we have chosen to explore Rh/Al_2O_3 steam reforming catalysts since this composition is known to be active over a larger operating range with a low sensitivity to poisoning by sulfur contaminants. The potential downside is that this catalyst system contains a relatively expensive precious metal, but this is somewhat offset by the very low loadings of the catalyst on the support (0.05 wt.% or less in the AER bed) required in the Absorption Enhanced Reforming system.

The goal of this task was to develop a highly active Rh/Al_2O_3 reforming catalyst that has Rh content of less than 0.05 wt.% when loaded in the AER bed either by reducing the amount of Rh on Al_2O_3 or reducing the amount of Rh/Al_2O_3 that is combined with the CaO-based CO_2 absorbent. The experimental work was focused on producing reforming catalysts by spray conversion that have a higher dispersion of Rh on different forms of Al_2O_3 with a variety of different surface areas and porosities to enhance gas transport. Variables that were explored included the type of chemical precursors to Rh, the type of Al_2O_3 support, the spray generation method as well as the temperature and time of spray processing. A series of characterization methods such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), BET and pore volume analysis, were conducted in order to correlate the catalyst performance with the precious metal loading, its dispersion and the overall catalyst porosity and stability.

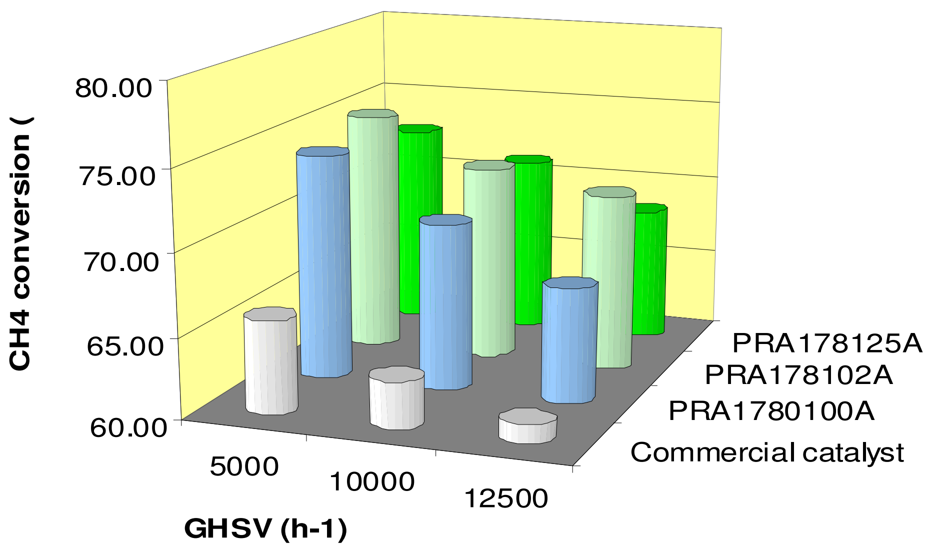
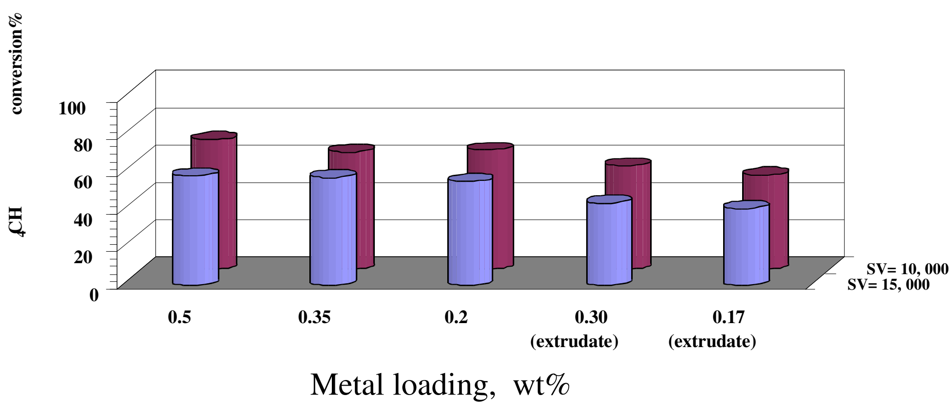


Figure 2: Steam reforming of methane over 0.5wt% Rh/Al203 catalysts

The activity of the powders in steam reforming of methane was measured at a reaction temperature of 600°C and a H_2O:C ratio of 3:1 (Figure 2). Compared to a standard commercially available reference catalyst with the same composition, the 0.5 wt.% Rh/Al_2O_3 catalysts made by the spray process show higher conversion at all space velocities. The catalyst activity of spray–based powders is clearly influenced by the spray processing temperature, Rh precursor type and solids loading in the precursor suspensions. These results clearly demonstrate the flexibility of spray processing for the preparation of reforming catalysts with higher catalytic activity, when compared to the catalyst prepared by a conventional approach.

To explore if further reduction of Rh loading is feasible without loss of performance, catalysts with lower wt.% Rh, 0.35 and 0.2 wt.% Rh/Al_20_3, were synthesized and tested for their methane conversion activity. Figure 3 compares the performance of lower wt. % Rh loading catalysts to this of 0.5 wt.%Rh/Al_20_3 catalyst, and with the activity of corresponding extrudates. It can be seen that even with 0.2 wt% Rh, the catalyst still demonstrates reasonable methane conversion as compared to the catalyst with loading of a 0.5wt% Rh/ Al_2O_3. These results indicate that spray processing as a method for producing the SMR catalysts, demonstrates a potential to reduce the precious metal content, while maintaining overall performance.



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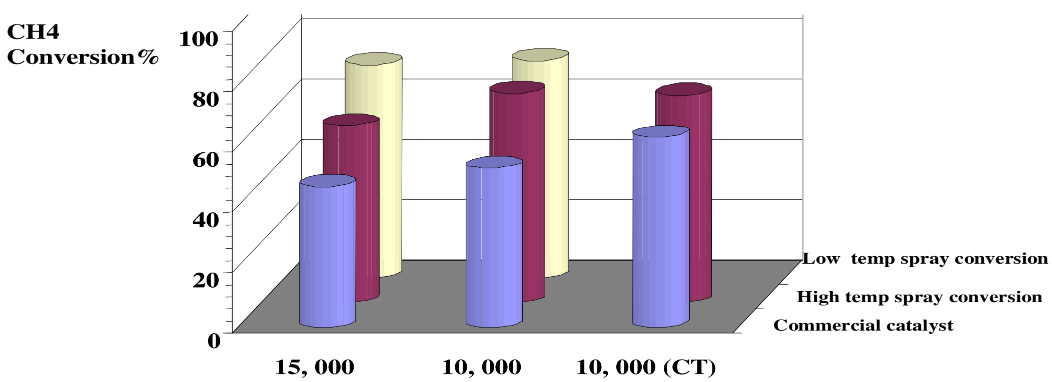


Figure 4: A comparison of the performance of reforming catalysts made by different spray conversion methods

A comparison of the catalytic performance of materials made by two different spray conversion approaches, high temperature spray conversion and low temperature spray conversion, were also conducted and the results are shown in Figure 4, together with test data for the standard commercial catalyst. The results demonstrate that reforming catalysts made by low temperature spray conversion can match and even exceed at higher space velocities the performance of powder made by high temperature spray conversion. The higher catalytic performance of Rh/Al_2O_3 materials made by spray conversion compared to the standard commercial catalyst has been assigned to a better dispersion of the precious metal over the support. Transmission Electron Microscopy (TEM) analysis was done for the samples made by spray methods vs. commercial sample. Figures 5 and 6 present TEM images for 0.5 wt.%Rh/Al_20_3 powders made by spray conversion (Figure 5) and conventional catalyst (Figure 6).

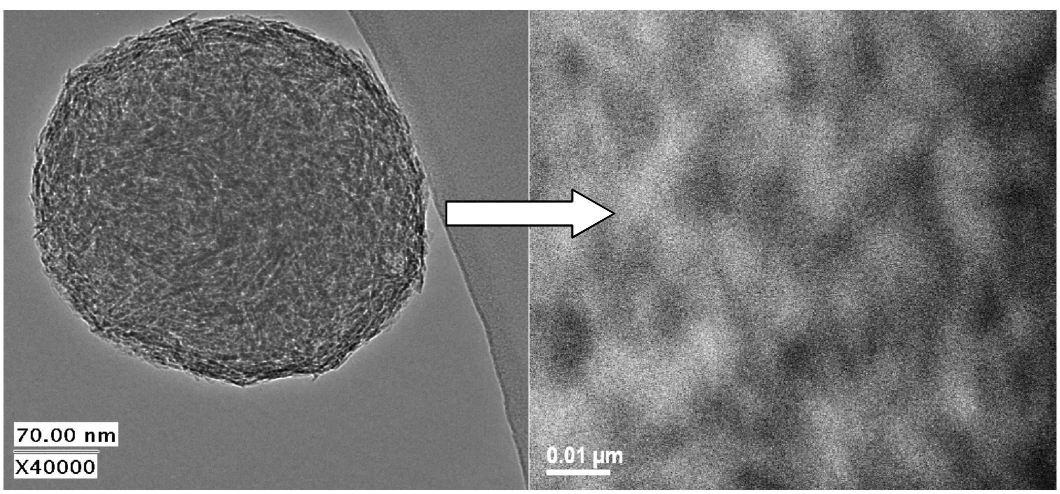


Figure 5: TEM image of 0.5wt% Rh/Al_2O_3 catalyst made by spray conversion

With the same loading, it is difficult to observe the presence of precious metal nanoparticles in the catalyst made by spray conversion (Figure 5), while Rh nanoparticles can be seen in the commercial Rh/Al_2O_3 at the same magnification (Figure 6).

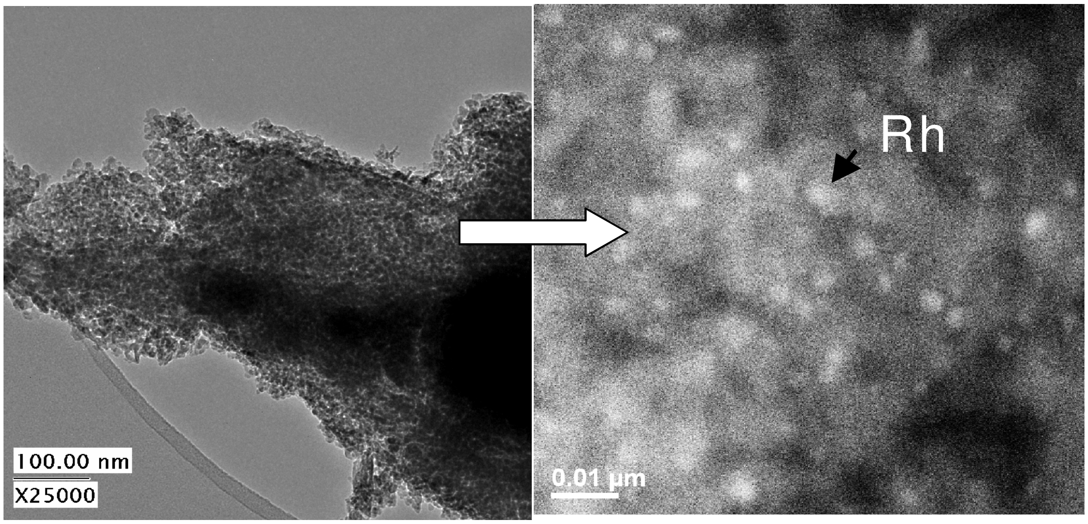


Figure 6: TEM image of 0.5wt% Rh/Al2O3 catalyst made by conventional method

The production of the Rh/Al_2O_3 catalysts was scaled up to quantities necessary for the reactor testing. An extrudates were also formulated with the reforming catalyst and tested in AER reactor. However, since the major materials developmental effort was focused on the sorbent optimization, and to minimize amount of variables, the testing in AER reactor was predominantly made with standard conventional reforming catalyst.

Subtask 1.2: CO_2 Absorbent

The work plan in this area was focused on the development of calcium oxide-based reversible CO_2 absorbents with various microstructures and morphologies to determine the optimum microstructure for long-term reversible CO_2 absorption. The effect of powder production process variables was systematically studied including: the final target compositions, the reagents from which the final products were derived, the pore forming additives, the processing time and temperature. The sorbent materials were characterized in terms of their performance in the reversible reaction with CO_2 and correlation made to their microstructure.

AER process and requirements for sorbent material

In the AER process the reactant, steam, and methane are introduced into a reactor containing a mixture of reforming catalyst and high temperature CO_2 removal sorbent. Once the sorbent is saturated with CO_2, forming $CaCO_3$, it has to be regenerated by heating it up to a higher temperature 750-850°C to convert it back to CaO. The process is therefore cyclic, and the reactor must undergo repetitive reaction/regeneration steps. The materials used in the AER process, both catalysts and sorbents, should therefore be capable of maintaining their activity (reactivity and capacity) and structural stability during multiple reaction/regeneration cycles. The key requirements for sorbent suitable for AER for high temperature CO_2 removal are:

- High CO_2 removal capability at high temperature
- Fast kinetics for reaction/regeneration in temperature range of 600-850°C
- Chemical stability, e.g. reversible CO_2 uptake/release
- Mechanical and thermal stability

It is known that natural or synthetic calcium oxide or dolomite could potentially be suitable absorbent material. However, the absorption capacity for these materials rapidly decreases during repeated CO_2 absorption-desorption cycles due to loss of porosity and sintering of crystallites. Therefore, a targeted design approach to the sorbent morphology and structure is necessary to achieve the stability targets during multiple cycles. Three main sorbent powder design aspects were explored:

1. Design the CO_2 reaction bed microstructure around the reacted form of the bed, such as $CaCO_3$. In this strategy, reversible reaction with CO_2 is less likely to close porosity and reduce surface area compared to designing the microstructure around CaO.

2. Execution of sequential chemical reactions involving specific reagents and pore forming chemicals performed by spray processing to produce discrete micron-sized particles comprising specific compositions and microstructures.

3. Integration of the sorbent powder with inert materials to achieve improved performance and stability of the final product. For example, introduction of soluble reagents such as $Mg(NO_3)_2$ in the starting solution will result in formation of synthetic tailored dolomite, while the introduction of nanophase Al_2O_3 will result in the formation of a CaO/Al_2O_3 composite.

A series of CaO and CaO-based materials were prepared by spray-based technology and some of the samples were further post processed by heat treatment following the spray conversion process. Four main types of materials with different composition were used for the initial investigation: CaO, Al_2O_3/CaO, CaO/MgO and Al_2O_3/CaO/MgO. The powders were produced by different spray conversion methods and different amount of additives (Table 2). For comparison, a commercially available CaO from J.T. Baker was used as a reference.

Sample ID	Composition	Precursors
A. CaO		
PCL178004A	CaO	CN, 20% NH4NO3, 2.5% PVP (10k)
PCX178091A	CaO	CN/latic acid/NH4NO3
PCX178092A	CaO	CN/NH4NO3
PCL178016A	CaO	CN/AO
PCL178019B	CaO	CN/AO
B. Al2O3/CaO		
PCL178019A	10wt% Al2O3/CaO	CN/AO/Al
PCL178019C	10wt% Al2O3/CaO	CN/AO/Al
PCL178019D	25wt% Al2O3/CaO	CN/AO/Al
C. CaO/MgO		
PCM178033C	CaO/MgO (90/10 wt/wt)	CN/AO+MN/AO
PCM178033A	CaO/MgO (50/50 wt/wt)	CN/AO+MN/AO
PCX178093A	CaO/MgO (50/50 mol/mol)	CN+MN/glycine/latic acid
PCX178095A	CaO/MgO (50/50 mol/mol)	CN+MN/urea/latic acid
PCX178096A	CaO/MgO (50/50 mol/mol)	CN+MN/glycine/ethanol
PCX178123A	CaO/MgO (50/50 mol/mol)	CN+MN/H2O
PCM185001A	CaO/MgO (52:48 mol/mol)	CN+MN/OA
D. Al2O3/CaO/MgO		
PCM178033D	5wt% Al2O3/CaO/MgO (90/10 wt/wt)	CN/AO+MN/AO+Al
PCM178033B	5wt% Al2O3/CaO/MgO (50/50 wt/wt)	CN/AO+MN/AO+Al

Note: CN: Calcium nitrate; MN: Magnesium nitrate; AO: ammonium oxalate; OA: oxalic acid

Table 2: Typical samples composition and the precursors used for making such material

Thermal Gravimetric Analysis (TGA) of the materials

Based on the material design concept, the sorbent materials containing low density CaC_2O_4 were first targeted. These types of materials were made with calcium nitrate and ammonium oxalate by spray conversion method. The analysis of the material thermal behavior was carried out by TGA. Figure 7 shows the typical TGA profile for as-made Ca-based powder from spray conversion with oxalate precursor.

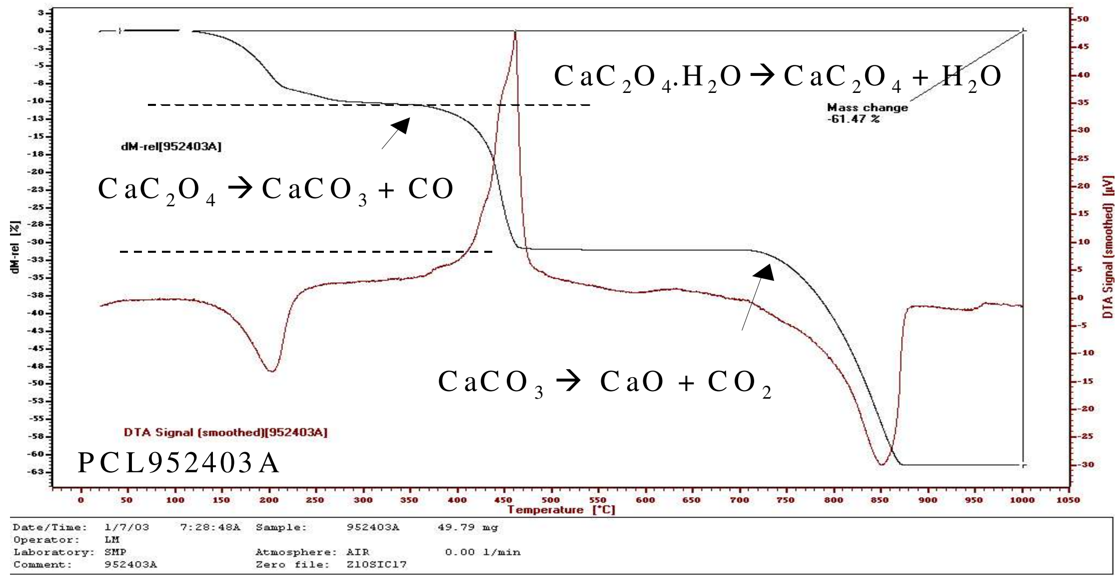


Figure 7: Typical TGA profile of Ca powder made by spray conversion with oxalate precursor

There are three major weight loss changes observed in the temperature range up to 900°C. Up to 250°C, there is a weight loss due to the dehydration, of about 10 wt%, the second range between 350 - 500°C, which accounts for about 19 wt% and is due to the decomposition of oxalate, and the third range from 700 - 870°C, with about 30% weight loss, which takes place because of decarbonation. Based on the literature survey and XRD analysis, the following chemical reaction is proposed during heat treatment process.

1. Dehydration
$CaC_2O_4.H_2O \rightarrow CaC_2O_4 + H_2O$ (up to 250°C)
$\Delta W1 = 12.3$ wt%

2. Decomposition
$CaC_2O_4 \rightarrow CaCO_3 + CO$ (350~500°C)
$\Delta W_2 = 21.85$ wt% based on CaC_2O_4; $\Delta W_T = 19.2$ wt% based on $CaC_2O_4.H_2O$

3. Decarbonation
$CaCO_3 \rightarrow CaO + CO_2$(700~860°C)
$\Delta W_3 = 44$ wt% based on $CaCO_3$; $\Delta WT = 30.1$wt% based on $CaC_2O_4.H_2O$

Total: $CaC_2O_4.H_2O = CaO + CO_2 + CO + H_2O$ (in the absence of O_2)

The total weight loss (theoretically) is 12.3+ 19.2+ 30.1=61.6 wt%, which is very close to the experimental TGA number of 61.5 wt%. From the TGA curve, it can also be seen that $CaCO_3$ can be stable in the temperature range from 500 - 700^{o}C.

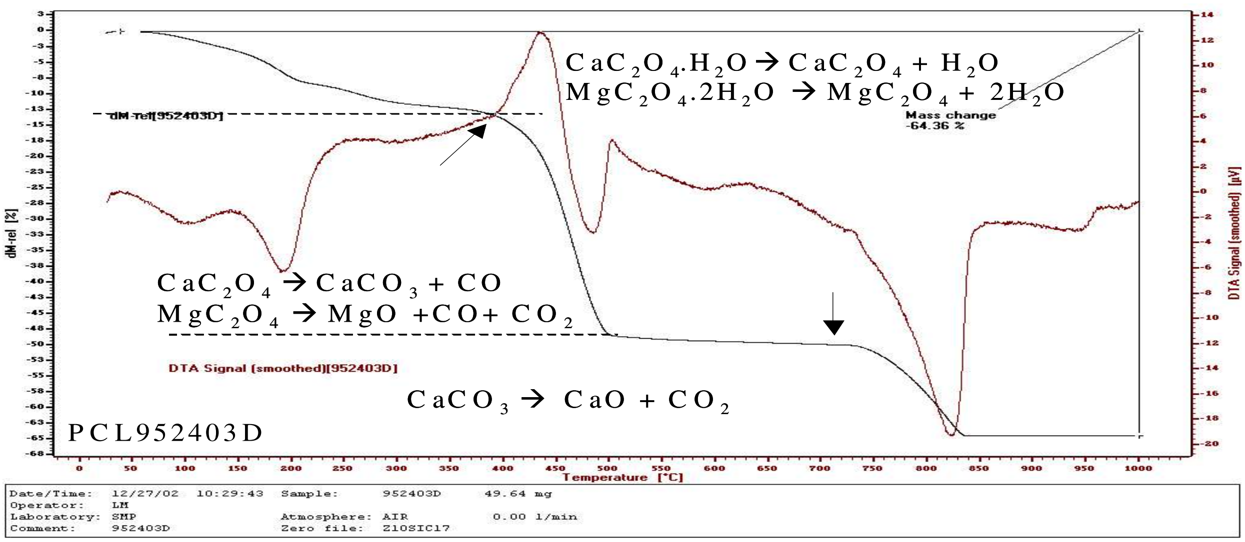


Figure 8: Typical TGA profile of CaOMgO powder made by spray conversion with oxalate precursor

The powder with a composition of mixed Ca and Mg oxalate was also analyzed by TGA and the profile was shown in Figure 8. Similarly, there are three major weight loss ranges in the temperature up to 900^{o}C. Up to 350^{o}C, there is a weight loss due to dehydration (13 wt%), and a second weight loss of about 35 wt.% between 350 - 500^{o}C was observed due to the decomposition of oxalate. The weight loss in the temperature range between 700 - 850^{o}C is due to the decarbonation of $CaCO_3$. The Ca/Mg oxalate demonstrates similar thermal behavior to Ca oxalate in the first stage (up to 350^{o}C) and the last stage (700 - 860^{o}C). However, during the second range, the TGA profile is quite different because the thermal stability of Mg oxalate and carbonate is much lower than the Ca material. In the temperature range of 350 - 500^{o}C, MgC_2O_4 is decomposed into MgO. The TGA analysis data were used for selection of post processing temperatures and conditions targeting particular a formation of a particular CaO compound and or a mixture of compounds.

A typical CO_2 absorption profile for a CaO-based sorbent is shown in Figure 9. The absorption process of a single cycle can be described with two mechanisms. A fast surface reaction step takes place initially, which leads to the formation of a carbonate layer; then the reaction advances with the diffusion of CO_2 through this carbonate layer and reacts the inner particle layer particle. This reaction step is controlled by the diffusion of CO_2 and its rate is

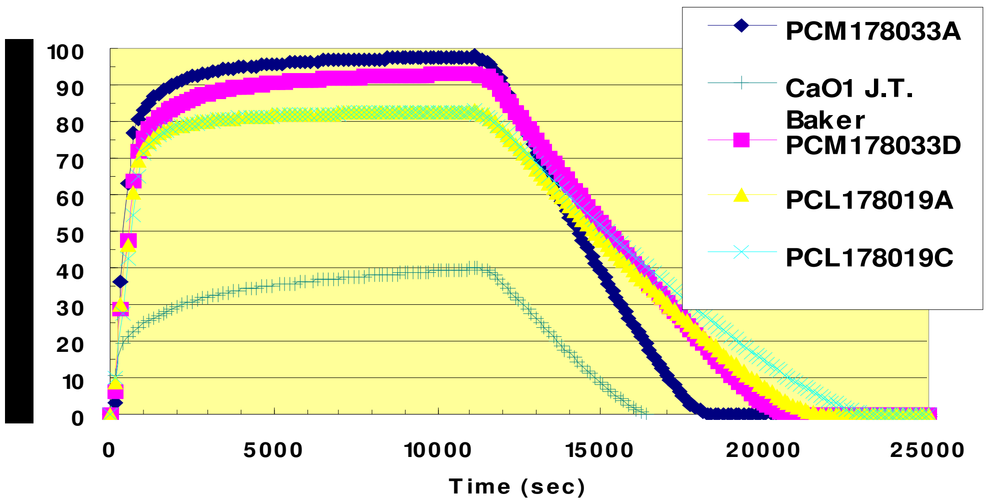


Figure 9: Typical CO2 absorption profile and regeneration over CaO sorbents as a function of time

significantly lower than that of the surface reaction. The absorption behavior observed is in agreement with the reports in the literature. All samples synthesized at different spray processing conditions and with various compositions were tested for their CO_2 absorption capacity during several cycles. Figure 10 compares the CaO absorption performance for CaO-based sorbent powders made by various spray processing methods (A and B) and commercial CaO powder during a limited cycle testing. The commercial CaO shows the lowest activity for CO_2 absorption and only converts 30~40 mol% of its total CaO into carbonate form. CaO powders produced by spray conversion method A are only slightly better. However, CaO powders made by spray conversion method B, followed by post processing, demonstrate the highest activity and more than 80% conversion. The cycling data, on the other hand, show a quick decrease of CO_2 activity from 80% to 35%, within only 8 cycles. This raised the question of how to sustain its initial high CO_2 capacity during cycling operations of absorption and regeneration.

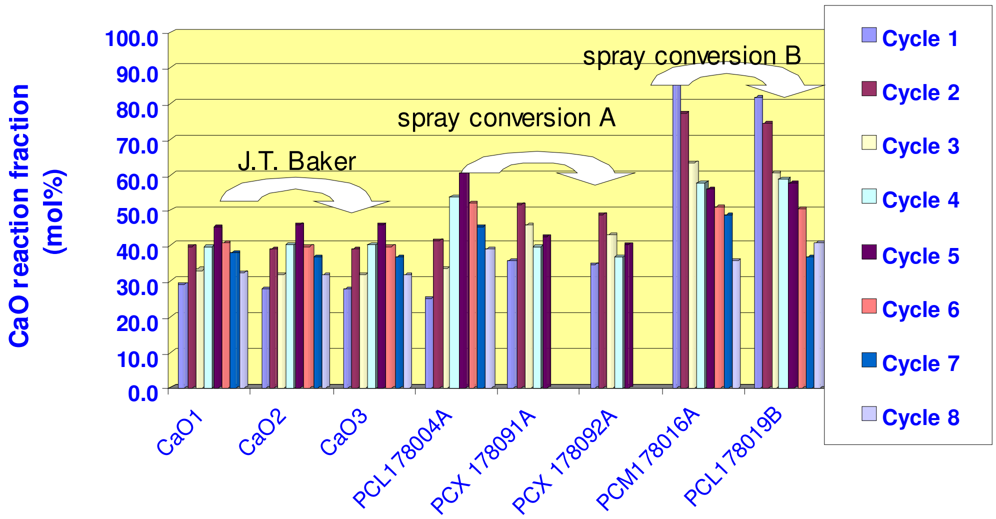


Figure 10: CaO reaction activity to CO_2 over CaO samples from different sources

Various characterization techniques were used to correlate the material performance with its physicochemical properties. Scanning Electron Microscopy (SEM) images, as shown in Figures 11 A and 11 B, suggest that powders morphology plays a significant role. The commercial CaO powder has a large particle size and is nonporous (Figure 11, A). The CaO powder made by spray conversion method B followed by post heat treatment has unique morphology with a small particle size and a very porous structure (Figure 11, B).

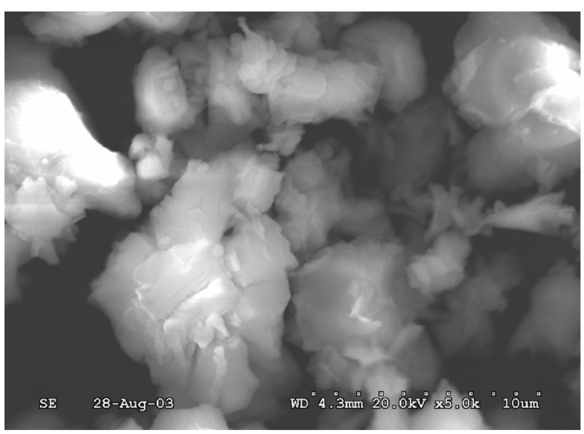


Figure 11,A: SEM image of the commercial J.T. Baker CaO

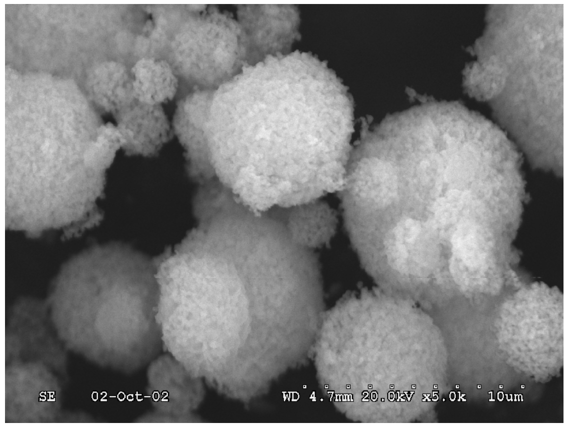


Figure 11,B: SEM image of CaO powder made by spray conversion method B

Further analysis of the particle size distribution, BET surface area, pore volume, and pore diameter of the CaO powders was performed and revealed that CaO powders made by spray conversion method B have small average particle size, significantly higher surface area and pore volume compared to the commercial CaO powder. These unique properties, particularly very porous structures, may provide for an easy access of CO_2 to the surface of the CaO particles, resulting in faster surface reaction activity, and accordingly, to a faster absorption kinetics as compared with other CaO powders, as seen in Figure 9.

The multiple cycle data for pure CaO samples in Figure 10, however, show quick loss of CO_2 capacity from 80% to 35% within only 8 cycles and demonstrate the long term durability challenge in the sorbent material design, i.e., how to sustain its CO_2 capacity during multiple cycles. To address this, large number of CaO-based powders with different additives such as Al_2O_3, MgO and combinations of MgO and Al_2O_3 were tested for their CO_2 sorption capacity over 10 cycles. The results demonstrate that by adding suitable amount of additives (based on the final material oxide composition) for CaO/MgO (MgO >10wt%), and Al_2O_3/CaO (Al_2O_3 <50%), the CaO-based materials not only demonstrate high initial performance but can also sustain its CO_2 capacity during the carbonation/decarbonation cycling. The CO_2 capacity during 10 cycles over selected Al_2O_3/CaO and CaO/MgO/Al_2O_3 samples are shown in Figure 12. For example, the spray based CaO/MgO (50/50 by weight) powder has initial activity of around 96% and after 12 cycles it still maintains over 90%. The CaO/Al_2O_3 (90/10 by weight), demonstrates around 78% capacity after 12 cycle test, practically unchanged from its original 80% capacity.

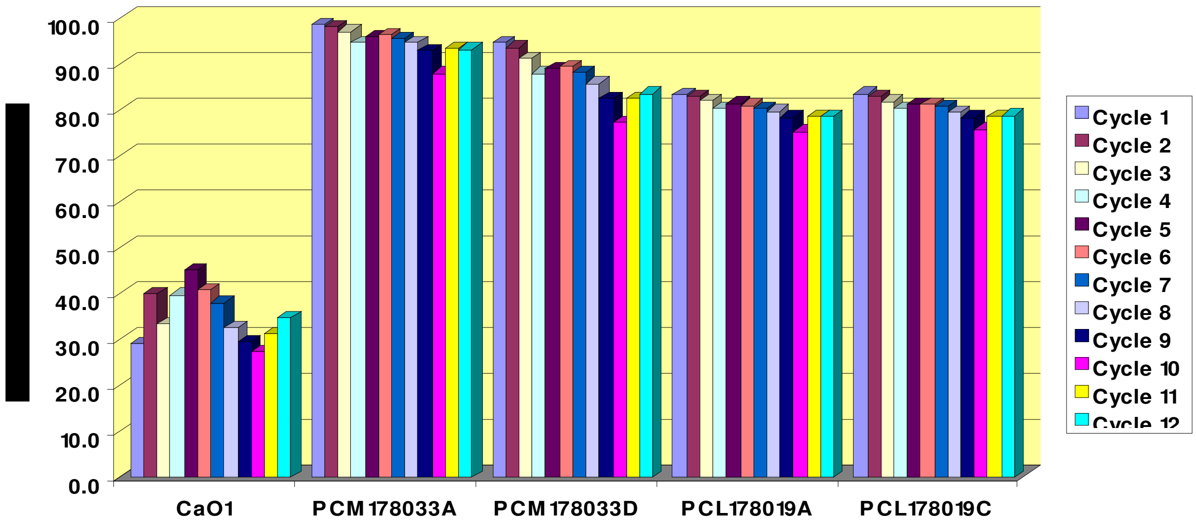


Figure 12: CO2 absorption capacity of selected CaO-based compositions: CaO1: pure CaO; PCM178033A: CaO/MgO (50/50 wt/wt); PCM178033D: CaO/MgO/Al2O3 (90/5/5 wt/wt); PCL178019A and 19C: CaO/Al2O3 (90/20 wt/wt)

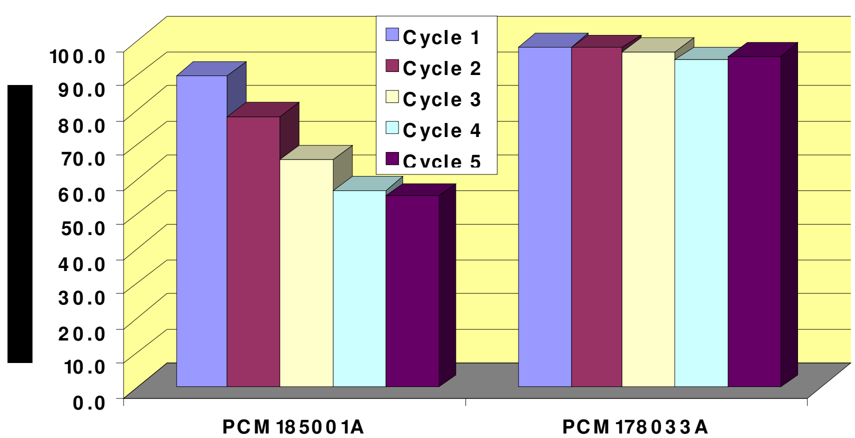
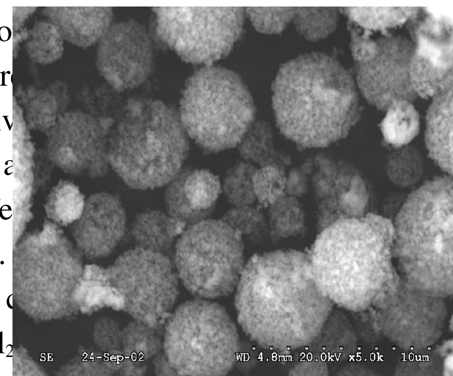


Figure 13: A comparison of CaO based sorbent performance between samples prepared by wet chemistry (PCM185001A) and spray conversion (PCM178033A)

The effect of different preparation methods on CaO/MgO CO_2 absorption performance by using the same precursor and powder composition were also investigated. One of the materials was prepared by conventional wet chemistry, and one with identical composition was prepared by spray conversion method. The CO_2 absorption data are provided in Figures 13. It can be seen that the CO_2 capacity decreases faster over the material made by conventional method, despite the identical composition. From the above comparison, it can be concluded that by using the unique material concepts and combining them with CSMP's proprietary spray technologies, a CO_2 sorbent powders can be synthesized with improved durability during multiple carbonation/decarbonation cycles. Analysis of the structural characteristics of these powders leads to the conclusion, that the incorporation of additives improves sorbent microstructure by increasing the surface area and pore volume, and prevents CaO particles from sintering.

Further optimization of the morphology and compo [illegible] materials was carried out. The effects of additives, temperatur [illegible] nt on CO_2 absorption performance were investigated. Additiv [illegible] e formers were used when making CaO/Al_2O_3 (90:10 wt/wt), a [illegible] 14. It can be seen that the use of fuel ethanol has positive effe [illegible] sulting in 10% higher than the material without any additives. [illegible] on of pore formers, and surfactants does not increase the CO_2 c [illegible] O_3 used as inert additive was also investigated. Different Al_2 [illegible] s such as crystallite size, BET surface area, and pore size were selected for making CaO/Al_2O_3 compositions and the most optimal for performance additive was selected.



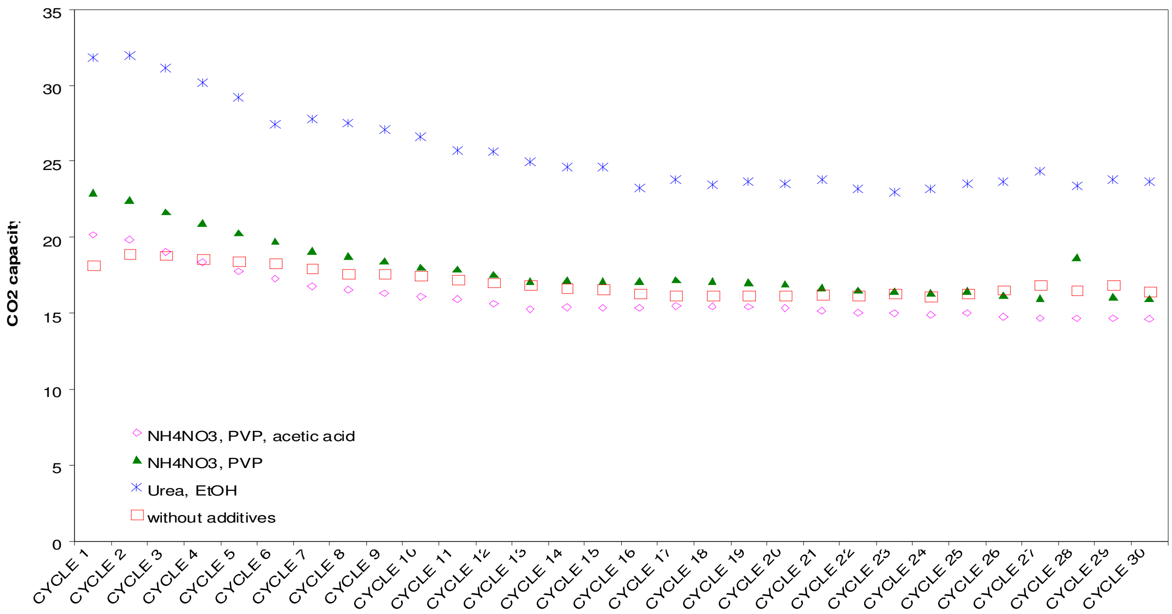


Figure 14: Effect of organic additives on the CaO/Al_2O_3 sorbent performance

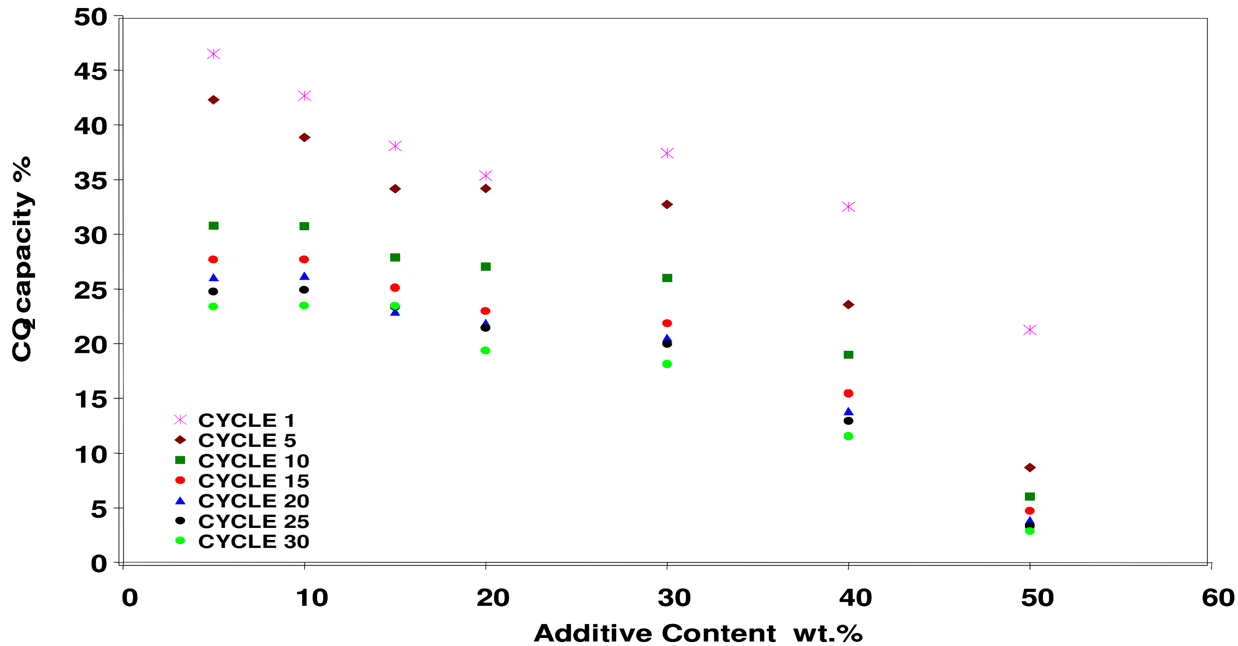


Figure 15: Effect of inert additive content on the sorbent capacity

The effect of inert additive content in CO_2 sorbent was also investigated with the goal to minimize its amount to ensure higher overall CO_2 capacity and maintain the required stability. Figure 15 clearly shows that when the inert additive is less than 30 wt%, the CO_2 capacity does not change significantly, while concentrations of inert additive higher than 30 wt.% have negative effect on the overall capacity and are undesirable. Figure 16 demonstrates the overall capacity for spray-based powders with various amounts of inert additive.

As a result of the extensive powders synthesis and testing for CO_2 capacity by TGA method, a number of powder compositions and post processing protocols were selected when the capacity and stability of the absorption were maximized. Among the best performing materials were the spray based powders with the following compositions: CaO:MgO, 50/50 wt.%,

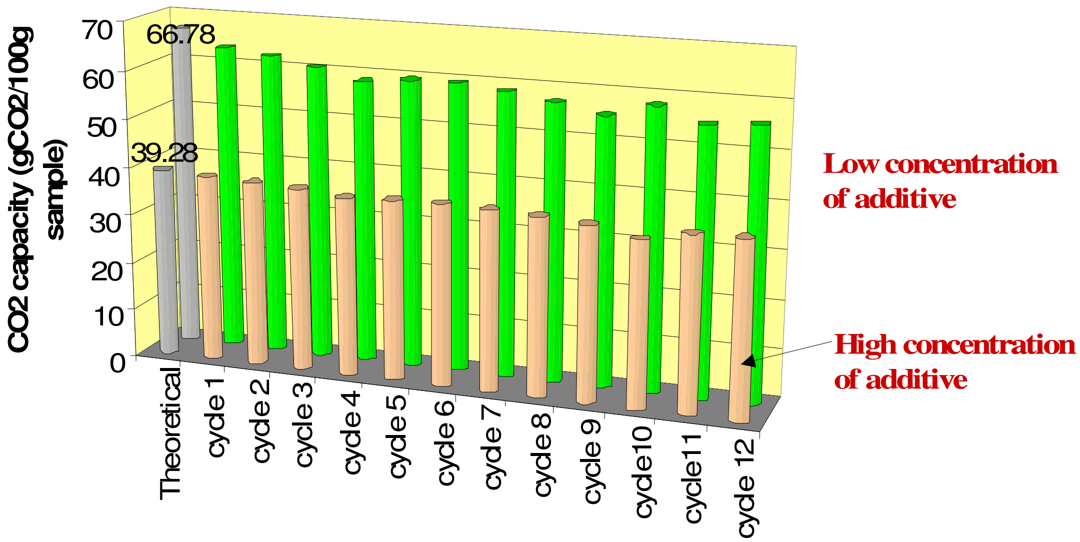


Figure 16: Comparison of CO_2 sorption capacity of spray based CaO powders with various amount of inert additives

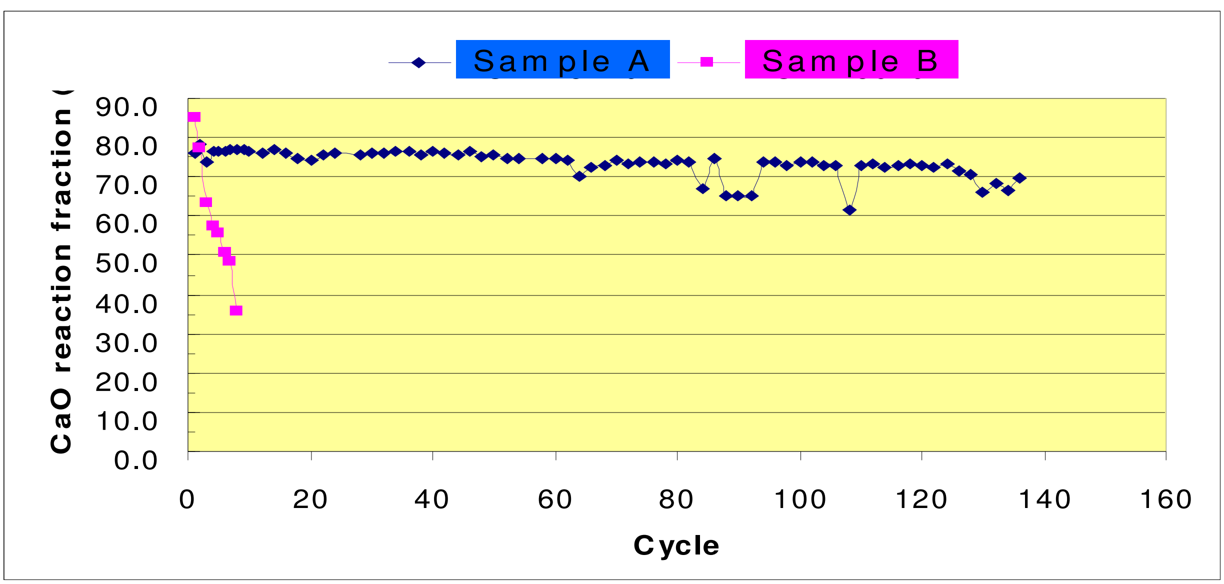


Figure 17: Long term cycling of spray based CaO powders evaluated by TGA CO_2 method

CaO:MgO, 80/20 wt.%, CaO:Al_2O_3, 90:10. Figure 17 shows an example of two samples with large variation in their sorption capacity and stability as measured by Thermo-gravimetric Analysis (TGA) under the following conditions: carbonation: 600°C; decarbonation: 750°C. These data show that the reactivity of the sorbents (in terms of CaO reaction fraction) of a properly designed material can be extremely high (over 70 % for sample A) and that it can be retained after multiple cycles of carbonation and decarbonation. To our knowledge this is the best performance observed for these type of materials and while this is only a relatively small number of cycles (over 140) at model testing conditions, it demonstrates the feasibility of the proposed materials approach. The spray-based powders, which demonstrated stability for over 100's of carbonation/decarbonation cycles were further tested for their CO_2 sorption capacity and stability when formulated into extrudates.

Note: Multiple samples described in the paragraphs above were produced and identified prior to the start of the project; however additional characterization and testing were completed during the execution of the project tasks.

Subtask 1.3: Pelletization

Based on the performance and characterization data measured for the powder materials in each of the Subtasks 1.1 and 1.2, optimum powder materials were selected for pelletization. The extrusion effort was focused on selected best catalyst and sorbent compositions. The work under this subtask was focused on the development of absorbent and catalyst-containing pellets with varying levels of contained binders and as a function of the pelletization processing conditions including amount of added binder, chemical reagent and thermal processing schemes.

For the sorbent and catalyst to be loaded into the AER fixed bed reactor, the catalyst and sorbent powder must be fabricated into shapes, such as extrudates, pellets or beads, (rather than original powders) in order to minimize issues such as pressure drop into the AER the reactor. Extrusion is the most commonly applied shaping technique for catalysts and supports. For extrusion, the catalyst/sorbent powder is generally in the form of wet paste or powder that is converted to a wet paste within the extrusion machine itself. The extrusion machine forces the paste through a die, and optionally cuts off the extruded material at the desired length. One of the minimum requirements is that the shaping process needs to minimize the loss of catalytic and sorption performance in the shaped extrudate/pellets. A series of the following criteria should be met for successful formulation of extrudates from the sorbent and reforming catalyst powders:

- The extrudate should have the required mechanical strength such as crush strength and attrition

- Since temperature swing operation (reaction/regeneration) and the use of stream are expected in the proposed AER process, the extrudate should have the necessary thermal and mechanical stability to withhold numerous cycles
- The extrudates should demonstrate high CO_2 absorption capacity and kinetics

A general extrusion recipe for catalyst materials was employed to make CaO-based powders into extrudates. Extruding equipment can be classified in one of the two categories: die/press extruders and screw extruders. Die extruders are used in general for highly viscous pastes; screw extruders are preferred for thixotropic products. In general, the ease of extrusion and quality of the product depend on the following properties of the paste:

1. Viscosity (adhesivity): A non-thixotropic product that is too viscous will block the extruder.
2. Thixotropy (fluidity): Certain substances become less viscous under shearing forces, and then recover their initial state after the forces have been released for a time called the relaxation time. The existence of such thixotropic properties is favorable for the flow of a paste and the formation of a solid granule at the exit of a die, providing the relaxation time is short enough.
3. Stability: Under extrusion conditions, there should be no dynamic sedimentation of the product through exuding water and forming paste that is too viscous.
4. Homogeneity: The paste must be homogeneous to assure that the quality of the product is constant. When necessary, the paste is homogenized in a mixer-kneader under controlled conditions of temperature, time, and pH.

Even for a given charge with specific properties, the operating variables are rather poorly defined and are closely related to the type of equipment. In general, they include: mixing time, water content, adhesives content, paste aging and extrusion temperature. In the case that a powder does not have certain level of fluidity or plasticity, one can add various additives to aid the pre-forming of pastes or microgranules such as lubricants, binders, peptizing agents and or pore formers.

Formulation of high crush strength CaO-based extrudates

High crush strength and attrition resistance are required for the catalyst/sorbent extrudate materials to be able to withstand long-term operation in AER reactors. A general rule of thumb for increasing the crush strength of metal oxide extrudates is to increase the concentration of binder into the pellets, which is detrimental to the absolute CO_2 sorption capacity since the binder is an inert material in regards to CO_2 absorption. Therefore an optimization of the amount of binder and sorbent is necessary to achieve both high physical strength of the pellets and high capacity towards CO_2 absorption.

Extensive effort was focused on the development and optimization of pelletization recipe and for scale up of the pelletization method. The following sets of experiments were performed.

- Evaluate various extrusion recipes with commercial CaO powders and spray-converted powders, over 50 various experiments with die and screw extrusion
- Fine-tune the extrusion recipe by:
    - Evaluation of various types of extrusion aid
    - Changing the way to use the extrusion aid
    - Changing the type and amount of binder
    - Study the effect of paste mixing sequence
    - Practice cutting equipment for the right length and dimension
- Extrude CSMP's spray-made CaO-based powders with modified extrusion recipe, over 100 various conditions experiments
- Design of experiments based on best performing compositions

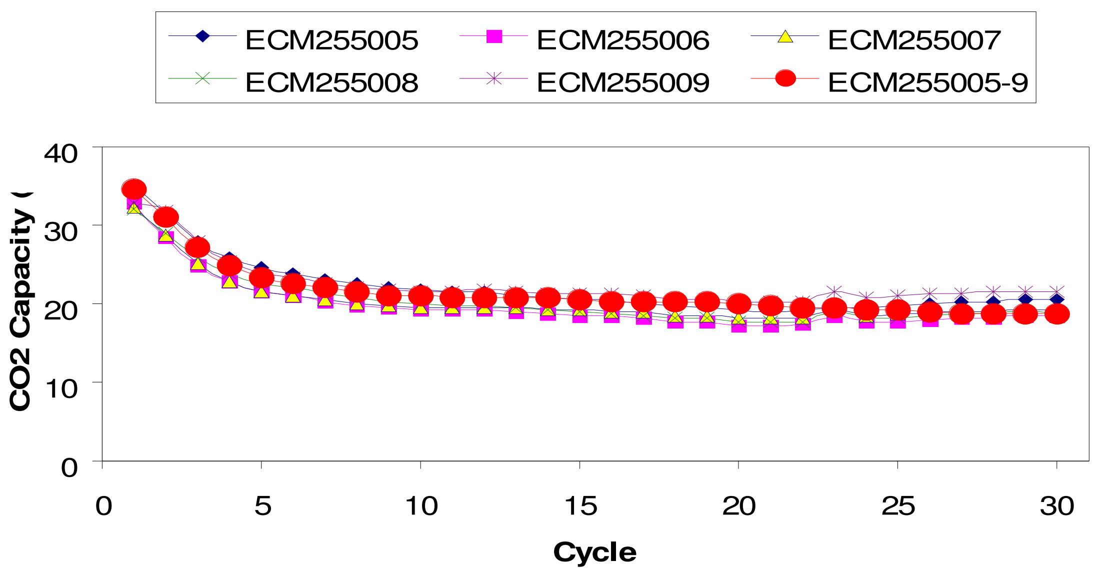


Figure 18: Cyclic CO2 - TGA of Repetitive Screw Extrusion

A 5 Liter (IP 5 AP/T) Lab Size Batch Mixer made by B&P with a working capacity of 3.5 liters (approx. 0.92 U.S. gallons) and 2” Lab Extruder made by the Bonnot Company were installed at CSMP and used for the R&D extrudate optimization and low-volume production requirements. For the extrudates produced by various procedures various characterization methods were employed such as evaluation of surface area, pore volume, crush strength and CO_2 absorption testing by rapid TGA testing protocol. In most cases at least 30 carbonation and decarbonation cycles were performed for each extrudate and initial and capacity at 30 cycles were compared. In many cases up to 120 cycles TGA testing were done.

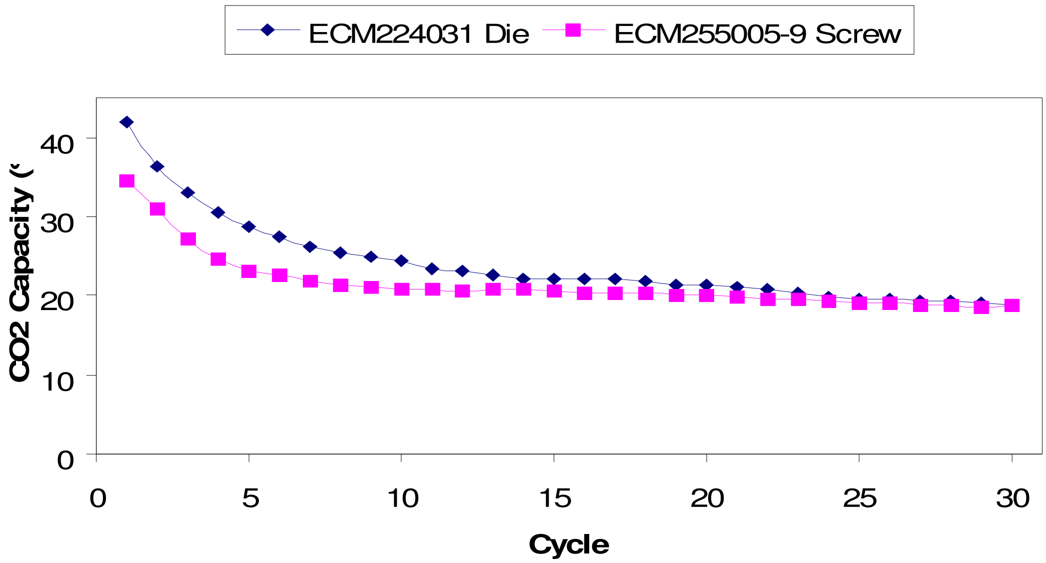


Figure 19: Cyclic CO_2 - TGA of Extrudate with CaO-MgO: 80wt% - 20wt%

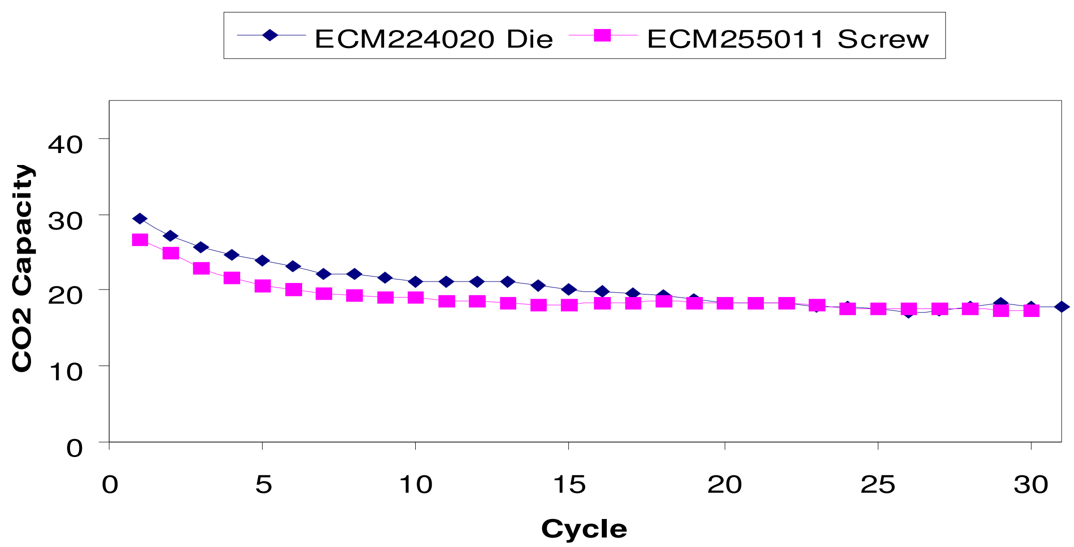


Figure 20: Cyclic CO_2 - TGA Extrudate with CaO - MgO: 58wt% - 42wt%

The screw extrusion experiments were done initially with commercial CaO powders and assisted in the development of original extrusion experiences with the CSMP's spray-made CaO-based sorbents. Over 100 batches of screw extruded paste with spray based powders were produced

and evaluated for their properties related to use in AER reactor and for improved understanding of the critical parameters influencing their performance and stability. Figure 18 shows cyclic CO_2-TGA of various batches of extrudates from identical as made powders, and demonstrates the reproducibility of CSMP's screw extrusion operation. Figures 19 and 20 show that for various powder compositions, extrudates made by screw extruder have similar long-term CO_2-sorption capacities as compared with extrudates made by extrusion in laboratory scale (die extrusion), which verifies that CSMP's extrusion is scalable without losing the superior powder performance.

Sample	Diameter	Test Items	1	2	3	4	5	6	7	8	9	10	Average	Deviation
		L (mm)	1.88	1.67	1.93	2.27	1.96	2.22	2.83	2.33	2.29	2.63		
ECM259004-1	0.06"	Force (DaN)	3.03	2.12	11.11	3.92	6.29	10.49	3.70	5.28	2.61	2.01		
C750		GCS (lb/mm)	**3.63**	**2.86**	**12.95**	**3.89**	**7.22**	**10.63**	**2.94**	**5.10**	**2.56**	**1.72**	5.35	3.75
		L (mm)	1.83	2.53	2.21	1.25	1.74	1.60	2.18	2.23	1.80	2.02		
ECM259004-2	0.05"	Force (DaN)	3.69	3.70	1.51	3.33	5.61	1.80	2.53	4.07	0.75	4.38		
C750		GCS (lb/mm)	**4.54**	**3.29**	**1.54**	**5.99**	**7.25**	**2.53**	**2.61**	**4.11**	**0.94**	**4.88**	3.77	2.05
		L (mm)	1.99	1.93	2.27	2.03	2.37	2.54	1.94	2.19	1.98	1.88		
ECM259004-3	0.04"	Force (DaN)	4.07	1.15	2.05	2.28	1.20	3.35	3.23	3.20	5.28	7.34		
C750		GCS (lb/mm)	**4.60**	**1.34**	**2.03**	**2.53**	**1.14**	**2.97**	**3.75**	**3.29**	**6.00**	**8.78**	3.64	1.56
		L (mm)	2.17	1.44	1.53	1.77	1.40	1.54	1.92					
ECM255055	0.05"	Force (DaN)	2.84	5.33	5.35	9.37	3.85	5.33	5.33					
C750		GCS (lb/mm)	**2.94**	**8.33**	**7.87**	**11.91**	**6.19**	**7.79**	**6.25**				7.32	2.71
		L (mm)	1.53	1.63	1.64	1.64	1.62	1.61	1.30					
ECM255055-2	0.04"	Force (DaN)	3.09	3.38	6.67	3.59	7.93	5.49	3.59					
C750		GCS (lb/mm)	**4.54**	**4.67**	**9.15**	**4.93**	**11.01**	**7.67**	**6.21**				6.88	2.50

Table 3: Crush Strength Tests of Extrudates with different Diameters

Table 3 compares the crush strength of extrudates of different diameter from same screw extrusion batches. There is a general trend that slightly bigger diameter extrudates have better average strength than smaller ones. The CO_2-sorption tests showed no major difference for same extrudates of various diameters. These results indicate that the diameter of the extrudates may need to be adjusted for specific project requirement, and if the crush strength and uniformity are dominant requirement, an adjustments of the screw extruder configuration may be necessary.

Comparison of scaled extrusion approach vs. benchmark extrudates performance.

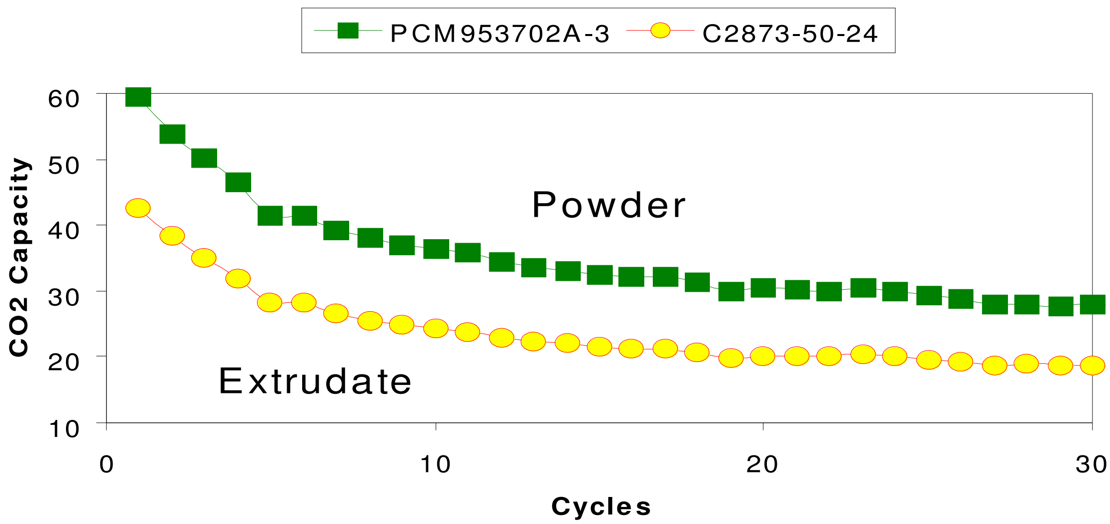


Figure 21: Cyclic CO_2 - TGA for Cao - Mgo: 80% - 20% benchmark powders and extrudates

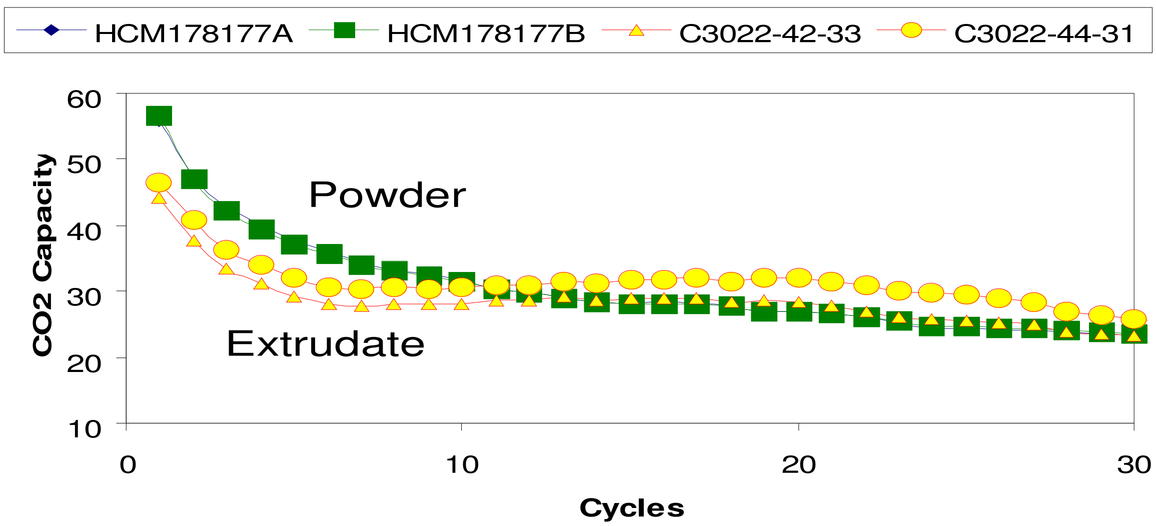


Figure 22: Cyclic CO2 - TGA for CaO - MgO: 80% - 20% benchmark powders and extrudates

Screw extrusion was done with powders with various compositions and their CO_2 capacity compared to this of benchmark extrudates All of the original powders used in the benchmark studies were made by CSMP's spray conversion, followed by similar post-processing treatments. Figures 21 and 22 compare the TGA CO_2 absorption data for benchmark

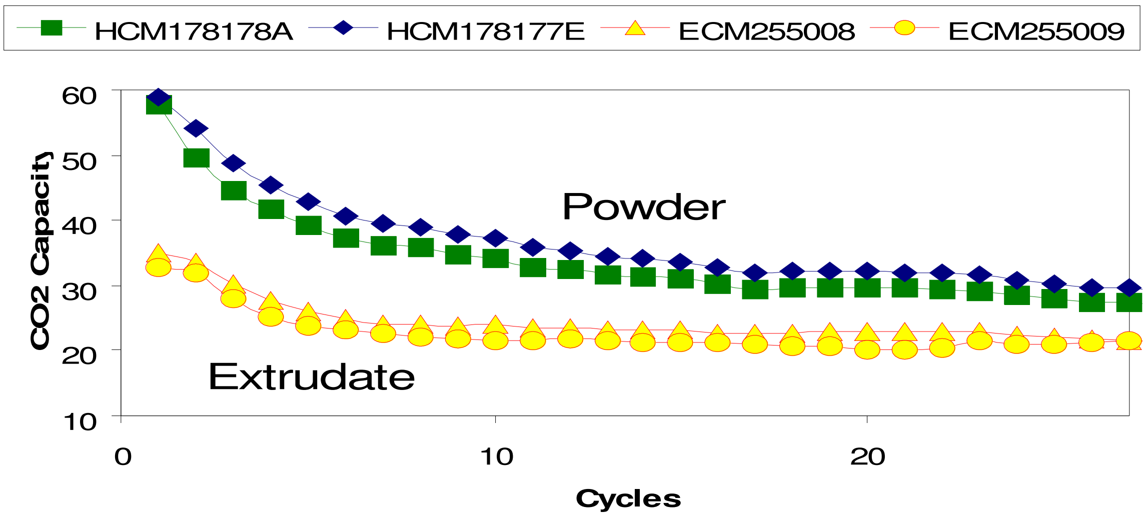


Figure 23: Cyclic CO2 - TGA for Cao - MgO: 80% - 20% powders and extrudates produced at CSMP by screw extrusion

CaO-based powders and the extrudates made with these powders. In one case, as shown Figure 21, the extrudates showed lower CO_2 capacity during cycling than that the starting powder, while in Figure 22, the extrudes showed comparable performance and even higher stability during cycling than the starting powder. The differences were assigned to different post processing conditions for the powders, extrusion procedure and heat treatment profiles for the extrudates. These results indicate that the pelletization procedure can have a significant impact on the performance and an effort was made to identify critical extrusion procedure parameters and optimize them.

Figure 23 shows the cyclic CO_2-sorption of screw extrudates made at CSMP, from similar original powders (CaO-MgO: 80%-20%). The extrudates show slightly lower capacity than the original powders similarly to the benchmark powders and extrudates (Figure 21).

In conclusion, screw extrusion method has been optimized and scaled up for spray-based CaO sorbent powders. Detailed studies of various extrusion parameters led to an operation procedure for production of large quantities of extrudates necessary for reactor testing. The overall sorption capacity for extrudates containing sorbent powders is lower compared to that of original powders due to addition of inert binder necessary to achieve stability and crush strength. It was identified that further studies are necessary to optimize the pelletization method developed for improved performance and stability of extrudates in reactor testing.

Optimization of scaled up formulation of sorbent extrudates.

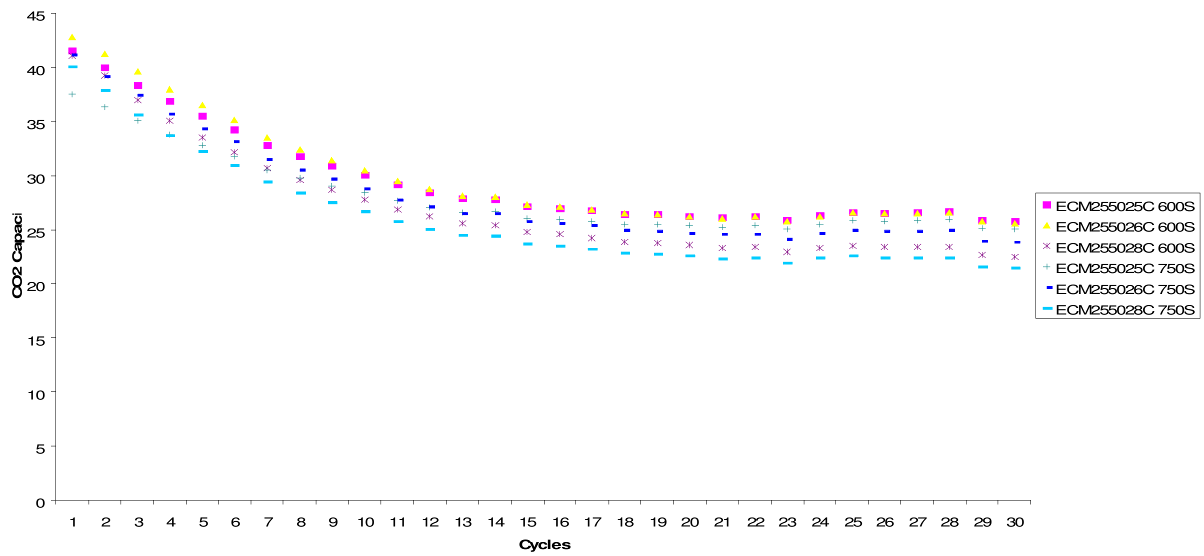


Figure 24: Cyclic CO_2 - TGA for extrudates based on $CaAl_2O_3$: 95%-5% powders produced at CSMP by screw extrusion

High crush strength and attrition resistance are required for the catalyst/sorbent extrudate materials to be able to withstand long-term operation in AER reactors. In order to achieve this goal, better paste mixing with suitable amount of binders, extrusion aids and water are critical. In addition, the extrudate calcinations conditions also play important role, since the CaO-based original powders are produced from low-density precursors such as carbonates, which as combined with the organic/inorganic extrusion aids are subject to continuous decomposition upon heat treatment before and after extrusion process.

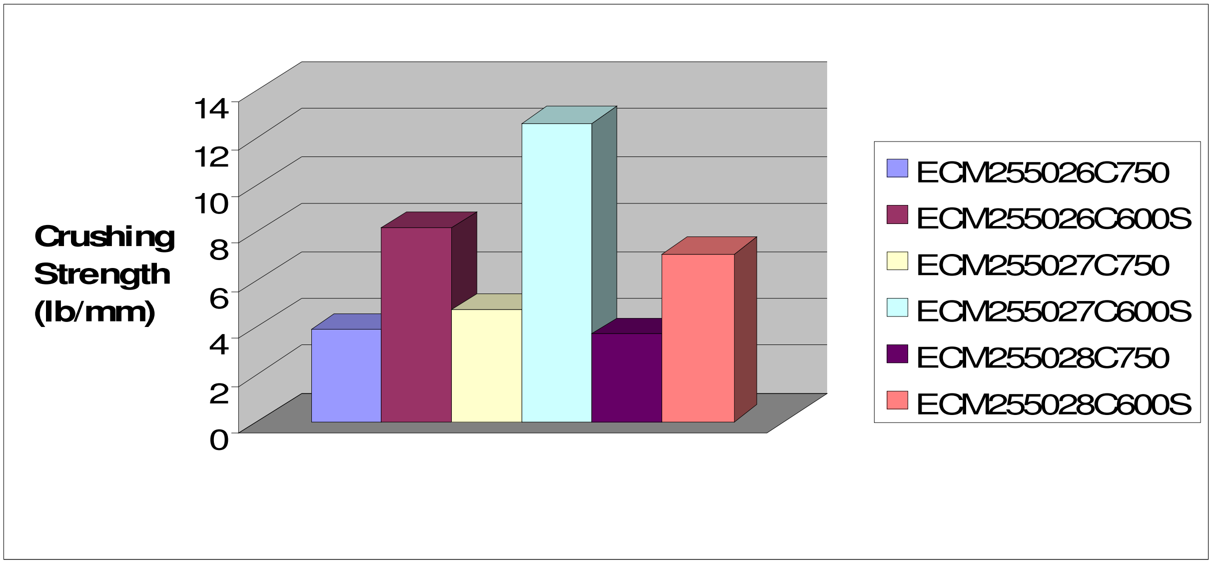


Figure 25: Crush strength of extrudates from powders (CaO-Al_2O_3: 95%-5%) calcined at various temperatures

A study on extrudate drying and calcinations conditions was performed and it was demonstrated that the CaO:Al_2O_3 sorbent extrudate drying and calcination procedures can be optimized substantially over the conventional procedures without reducing crush strength or resulting CO_2-TGA performance. The parameters analyzed were: drying procedure, calcinations procedure and corresponding temperature profiles. These studies were further extended to larger quantities of extrudates subjected to various drying/calcinations profiles. These study showed that the calcinations temperature has an effect on the extrudates initial crush strength and other physical properties such as packing density and surface area, but does not affect significantly the TGA CO_2 sorption performance. Figures 24 and 25 show the effects of extrudate calcination temperature on the CO_2 sorption capacity (Figure 24) and crush strength (Figure 25). The effect of the extrudate calcinations temperature on CO_2 sorption performance is negligible. However, there is significant impact of the calcination temperature on the extrudates initial crush strength value, as seen in Figure 25, the higher calcinations temperature (750°C) results in lower strength than extrudate calcinations of 600°C.

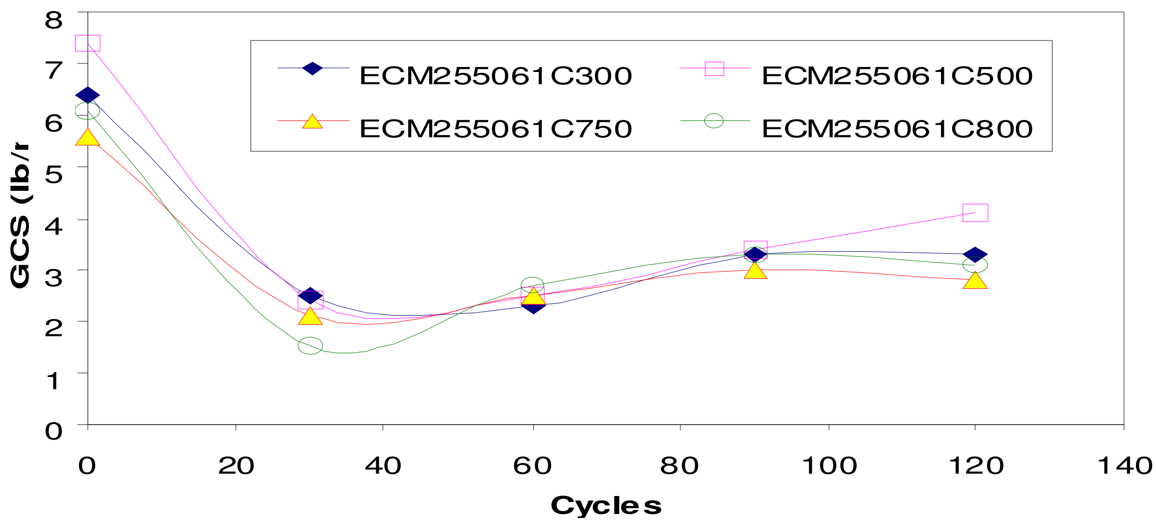


Figure 26: Crush strength of extrudates after TGA CO_2 cycling

Figure 27: SEM image of CSMP extrudate after 523 carbonation / decarbonation cycles in the TGA CO_2 testing

Further analysis of the sorption capacity and the crush strength as a function of the number of cycles (up to 120 cycles of TGA CO_2 absorption) was performed and presented in Figure 26. During the TGA CO_2 sorption cycling, both the capacity and crush strength decline significantly for the first 20-30 cycles, but then stabilize thereafter. The crush strength is generally higher than 2 lbs/mm after 100 cycles, regardless of the specific extrudates calcination temperature. This indicates that extrusion procedure developed provides effective ways to produce CaO- based sorbents that can withstand the severe thermal cycling conditions under TGA cycling model test. The developed extrudate formulation procedure was demonstrated to deliver extrudates that sustain their mechanical integrity under thermal cycling used in the TGA CO_2 sorption test experiments as demonstrated in Figure 27. Both spray powder composition and extrudate formulation were established to be an important factor for the stability of the extrudates. Further testing in AER reactor conditions (in the presence of steam in addition to the thermal cycling) remains to be completed for multiple cycles to establish the long-term durability of the developed powder and extrudate formulations.

Subtask 1.4: **Integration of Materials for AER Reforming**

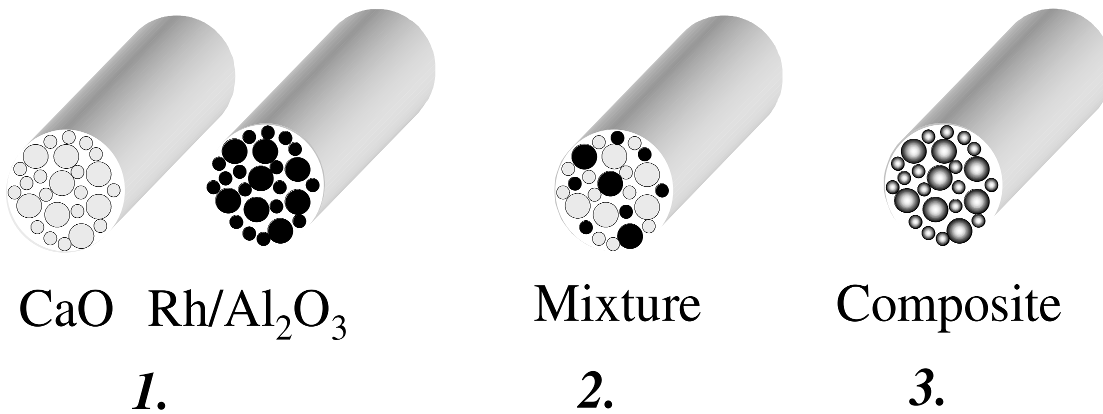


Figure 28: Schematic representations of the different pellet structures that will be produced to achieve different spatial segregation of the CaO-based absorbents and steam reforming catalyst

The materials developed in Tasks 1.1-1.3, e.g. CO_2 sorbent and reforming catalyst, can be combined in a number of different ways to achieve the most efficient absorption-enhanced reforming. The integration of the catalysts and CO_2 absorbents can be done at length scales between mm and nm as described in Figure 28. The work plan was targeting to maintain the performance of the individual materials while ensuring that the materials can be mixed and pelletized as described above. It was considered, that the advantages of the second and third approaches over the first may be that mixing of the sorbent and reforming catalyst powders within each pellet can enable a much closer spatial proximity on the order of 10s to 100s of microns.

The first approach analyzed was by combining individual pellets of Rh/Al_2O_3 and CaO-based CO_2 absorbent derived from the best materials from Task 1.1-1.3 with a goal of reducing the Rh content below 0.05 wt%. In this approach, there is no intimate contact between the catalytically active sites and the sites of CO_2 absorption, the proximity of these species being limited by their relative concentrations and the pellet sizes. This approach has been predominantly used in the AER reactor testing and has been successfully demonstrated.

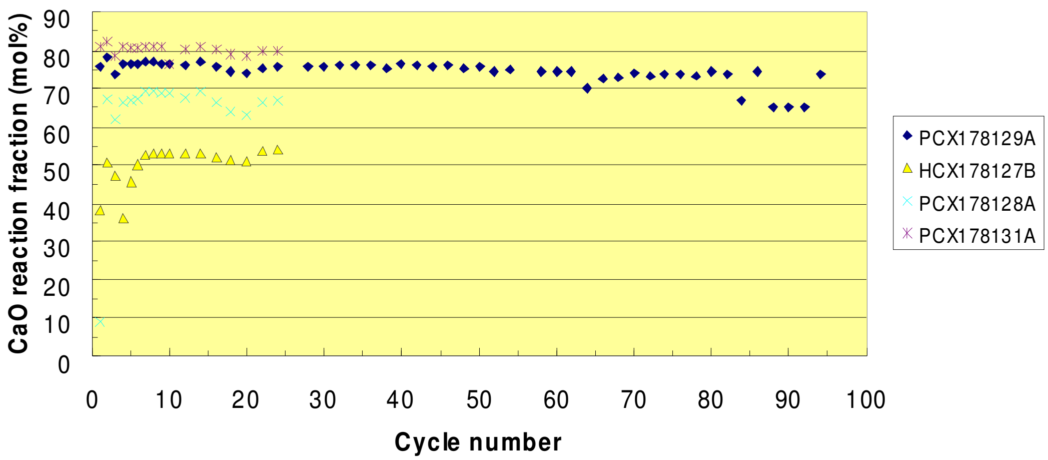


Figure 29: A comparion of the composite powders performance during multiple TGA cycling

In the second approach (Figure 28, Part 2), the powders of the individual Rh/Al_2O_3 and CaO-based CO_2 absorbents were mixed and pelletized together. This approach was demonstrated to deliver initial performance at AER reactor conditions but further experiments were not attempted because of lack of particular advantage.

In the third approach, the Rh/Al_2O_3 and CaO-based absorbent were mixed into a single composite powder batch where these materials both occur within the same particle. A composite powder material was prepared by the spray conversion method with the composition of CaO/MgO (90:10wt/wt) plus 10 wt% of Rh/Al_2O_3 (Rh 0.5wt% on Al_2O_3). TGA cycling testing demonstrated (Figure 29) that the material has reasonable CO_2 capacity and good cycle ability. However, the AER testing results were not promising and assigned to the lack of sufficient reforming activity. This may have been caused by the catalyst phase sintering and solid-state phase transformation and/or encapsulation of the active metal phase, or by the covering of the reforming catalyst active sites during carbonation. Therefore, further efforts on the integrated materials development were focused on the development of pellets of the individual components (sorbent and reforming catalyst).

Subtask 1.5: Improved Carbonation/Decarbonation Kinetics

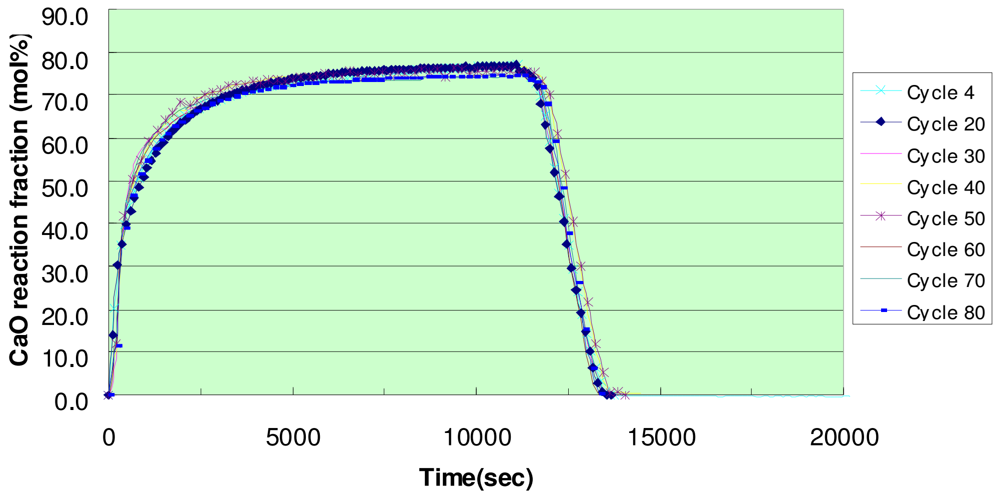


Figure 30: Carbonation / decarbonation profiles of CaO-based powder

Two materials strategies were examined as part of this task. It has been demonstrated that the microstructure of the CaO powders can affect the rate of decarbonation. The increase in the rate of decarbonation has been observed as the morphology of the sorbent powder (particle size and porosity) was changed as result of the spray processing conditions (see Figure 30). Fast decarbonation rates are desirable for efficient AER process.

Subtask 1.6: Integration of Water Gas Shift (WGS) Catalysts

The initial plan for this task was targeting incorporation of sufficient amounts of high-temperature water gas shift catalyst to ensure the conversion rates of CO to CO_2 will be sufficient. After further analysis of the thermodynamics of the AER process and literature data, it was concluded that in the AER operating conditions, the high conversion of carbon monoxide to hydrogen (> thermodynamics equilibrium) could be achieved in the absence of a WGS catalyst when one of the product products (CO_2) is removed from the reaction zone by its reaction with CaO. This indicated that reforming and Water Gas Shift reaction /CO_2 fixing can be combined in the AER process and it is not necessary to have separate WGS catalyst functionality.

Task 2: Catalyst and CO_2 Absorbent Performance Testing

Subtask 2.1: Screening of Materials

The initial screening of the new materials was done by the following methods.

- **Rh/Al_2O_3 reforming catalyst testing**
  Rh/Al_2O_3 materials made by different strategies were tested for their reforming activity. CSMP conducted initial reforming activity testing for down selection of materials to be further tested by TES in AER reactor.
- **CaO-based absorbents testing**

CSMP conducted extensive testing by Thermo Gravimetric Analysis (TGA) of sorbent powders during multiple cycles of carbonation/decarbonation. Both short and long term testing protocols were used for evaluation of the sorption capacity, kinetics and long-term durability of the sorbent powders and extrudates.

Subtask 2.2: Short Term Cycle Tests

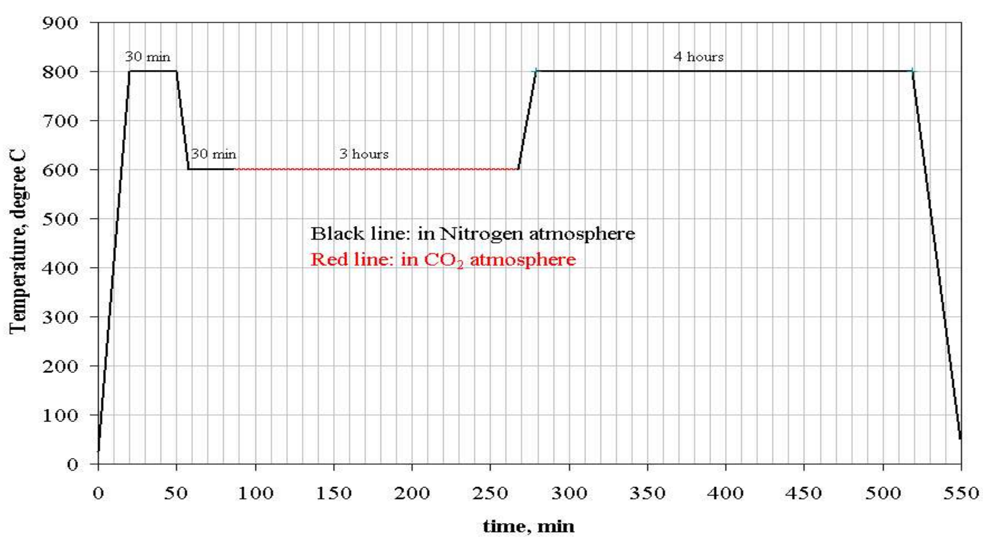


Figure 31: Design of CO2 - TGA protocol

Evaluation of sorbent performance and CO_2-TGA testing protocol:

Thermo Gravimetric Analysis (TGA) equipment produced by Leco Company was used as the major tool for fast screening of the sorbents. This TGA equipment can hold up to 19 samples and measure the sample weight change at intervals of seconds through rotation. Two methods were used to measure sorbent reactivity. One is CaO molar reaction fraction (mol%), defined as the number of mol of CaO in the sample converted into $CaCO_3$, regardless of the presence of other components. Another was the CO_2 absorption capacity (wt%), defined as the amount of CO_2 absorbed into the sample based on the total given weight sample. They are expressed as:

- CaO reaction fraction (mol%) = Converted CaO into $CaCO_3$/Total molar number of CaO in the sample * 100%
- CO_2 absorption capacity (wt%) = Absorbed CO_2/Total weight of the sample * 100%.

The CO_2-TGA testing protocol for one cycle is shown in Figure 31. A typical amount of sample (~1.0g) was loaded into a crucible in a TGA unit and was heated from room temperature at a ramp of ~40^{o}C/min to 800^{o}C under the N_2 or air flow condition of 4L/min, then held at this temperature for 30mins. It was then cooled to 600^{o}C and held for 30mins at these conditions to ensure stable baseline. This was followed by introduction of CO_2 to start the absorption; after 3 hours the gas is switched back into N_2 or air and the sample was heated up at 10^{o}C/min from 600 to 800^{o}C. The sample was kept at the final temperature for 4 hours, and then naturally cooled to room temperature. This process was repeated until the appropriate number of cycles was generated. All data points for performance evaluation were taken at/after 10,000th second.

Subtask 2.3: Long Term Cycle Tests

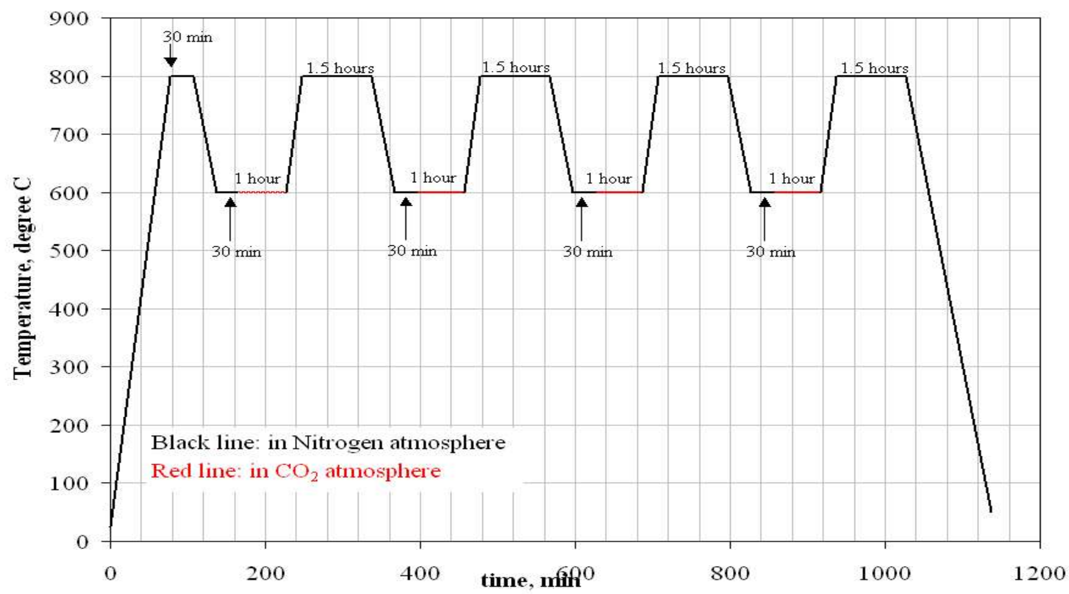


Figure 32: Design of new rapid CO2 - TGA testing protocol

New rapid CO_2 absorption TGA testing protocol was developed to address the need to evaluate multiple 100's of cycles and to probe mostly the fast CO_2 absorption region of the overall CO_2 absorption profile, which is most relevant for the AER reactor operating conditions. Thus, a new TGA model testing protocol was developed to more closely reflect AER process temperature profiles (Figure 32).

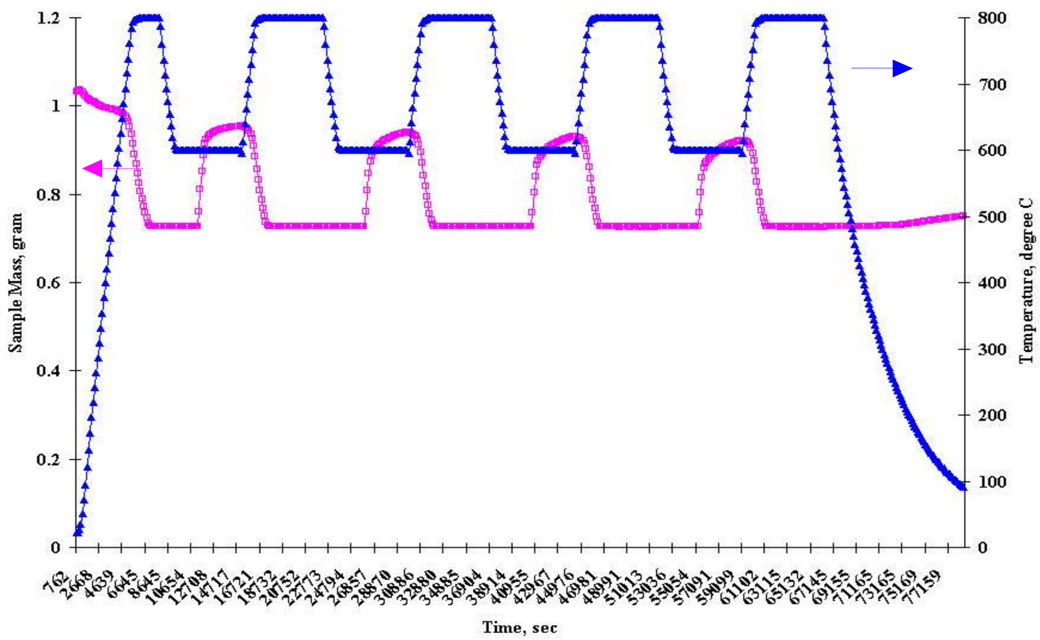


Figure 33: CO2 - TGA profile of CaO:MgO sorbent with continuous cycling testing

A typical amount of sample (~1.0g) loaded into the crucible in a TGA unit is heated from room temperature at a ramp of ~40^{o}C/min to 800^{o}C under the N2 or air flow conditions of 4L/min, then held at this temperature for 30 min. The sample is then cooled to 600°C and held at steady condition for 30 min to ensure stable baseline. The gas is then switched into CO_2 to start the absorption, after 1 hour, the gas is switched back into N_2 or air. At the same time, the sample is heated to 10°C/min from 600° to 800°C, and kept at the final temperature for 1.5 hr. It is then cooled down to 600°C, and held steady at this temperature for 30 minutes to ensure stable baseline, then the above procedure is repeated. The process is highly automated and can be performed for extended time. The program was set up for 30 cycles before it was stopped for the purpose of data analysis, and equipment maintenance. At this point, the sorbent samples were cooled down to room temperature. Figure 33 shows the real running program and the typical results of CaO/MgO (50:50 wt/wt) sorbent extrudate over four-cycle run. It can be seen that the regeneration can be complete during the one and a half hour regeneration period.

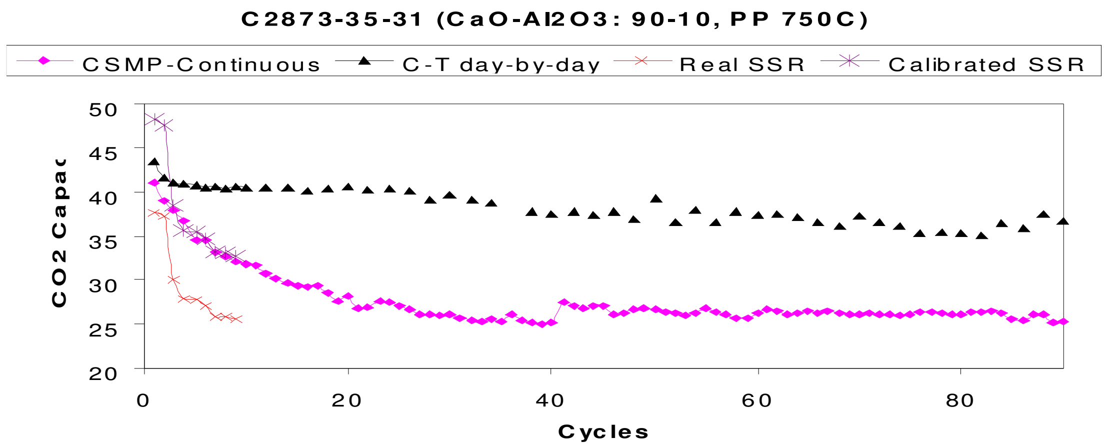


Figure 34: Correlation of CO2 capacity of the extrudates measured by different methods with AER results

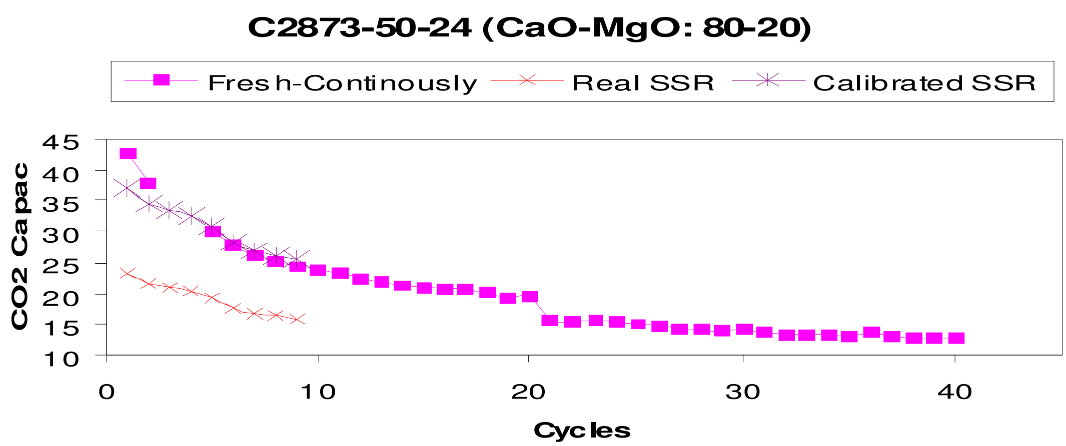


Figure 35: Correlation of CO2 capacity of the extrudates measured by different methods with AER results

An analysis was done to evaluate if the CO_2 capacity obtained in the fast absorption region by the new TGA testing protocol can more accurately reflect the sorbent behavior in the AER process. A series of data from CO_2-TGA measurements were correlated with the limited number of cycles by AER reactor testing, as seen in Figures 34, 35, 36. From the comparison, it is evident that for some extrudates the TGA data correlate very well with AER data (Figure 34, 35), while others show larger deviation and surprisingly higher performance in the AER reactor compared to the model testing (Figure 36). The reasons for these discrepancies result partially from the fact that CO_2-TGA measurement conditions still do not fully match the AER process conditions such as the presence of steam, a partial pressure of CO_2, and the running space velocity. However, the new rapid testing protocol is capable of evaluating the initial drop of sorption capacity and is valuable method for rapid testing and prescreening of sorbent materials before further testing in the AER reactors.

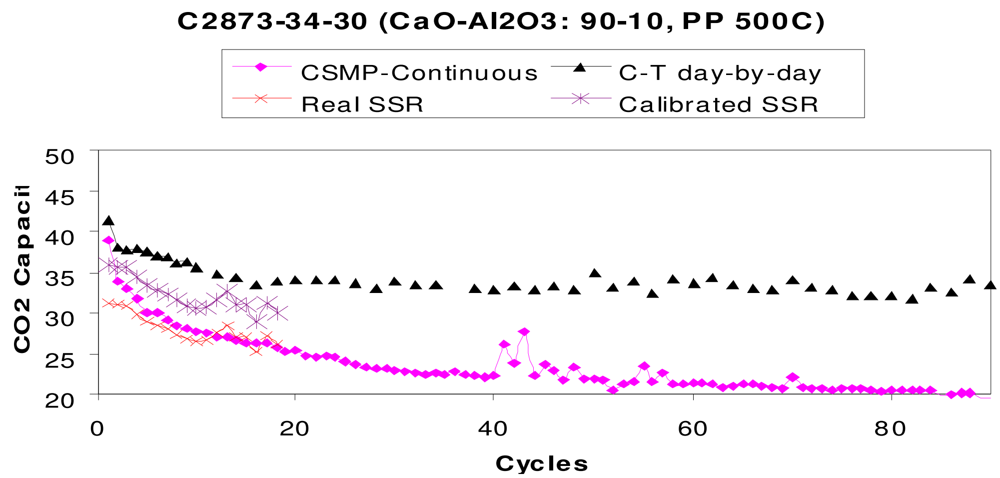


Figure 36: Correlation of CO2 capacity of the extrudates measured by different methods with AER results

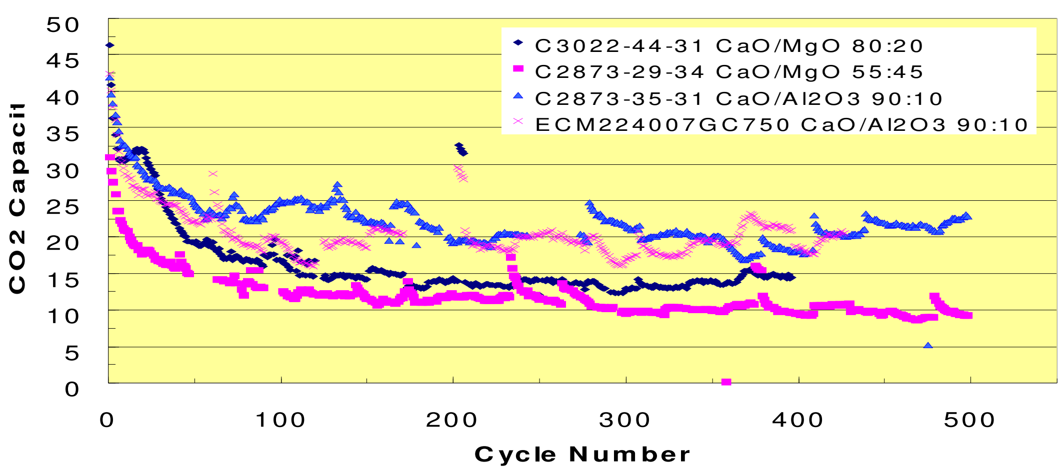


Figure 37: Long term TGA CO2 capacity of sorbent extrudates

Therefore, the new test protocol was employed for long term recycle ability testing. For selected best performing extrudate compositions (CaO/Al_2O_3 (90:10 wt/wt), CaO/MgO (80:20 wt/wt), and CaO/MgO (50:50 wt/wt). over 500 testing cycles of TGA CO_2 were carried out. The results are shown in Figure 37. It can be seen that after an initial decline of the CO_2 capacity within the first 50 to 100 cycles, the sorbents structure stabilizes and loss of sorption capacity is minimal.

In order to evaluate the potential loss of capacity over multiple cycles, a curve fitting based on model consideration was conducted. The experimental data for various sorbent extrudates were curve fitted and specific degradation constants derived for each of the sorbent compositions (examples presented in Figures 38 and 39). The results were summarized in Table 4, where the final sorption capacity and predicted capacity after more than 4,000 cycles (equivalent of one year reactor operation) are summarized as function of the sorbent composition.

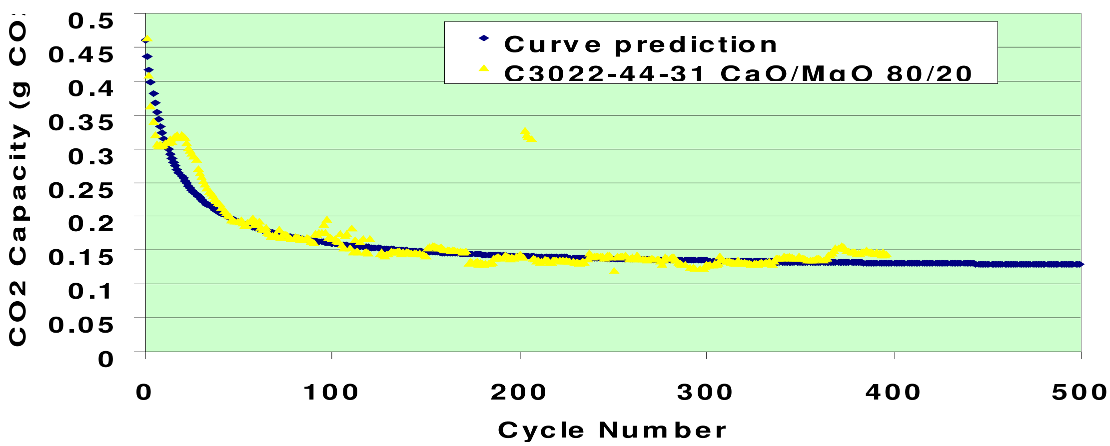


Figure 38: Correlation of experimental CO2 capacity over multiple cycles and model curve fit

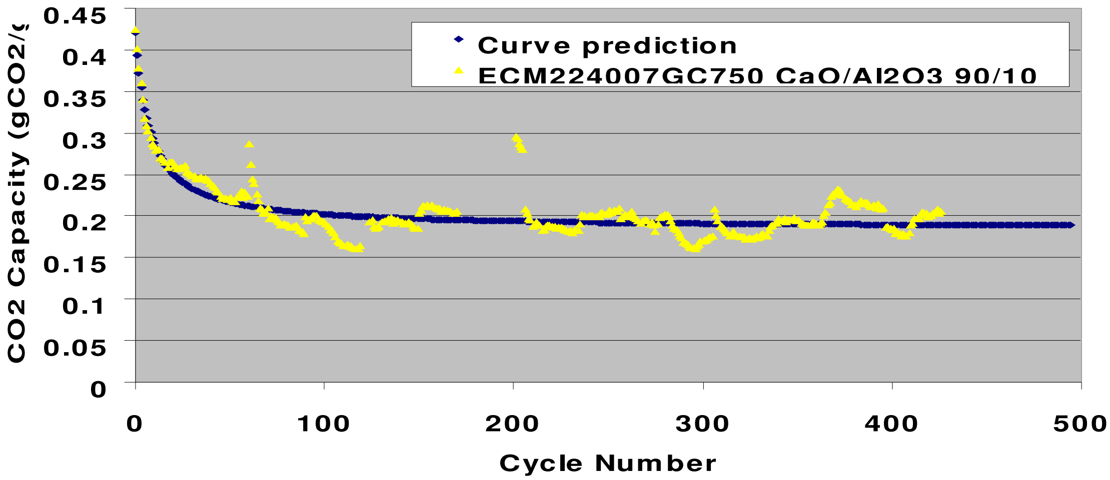


Figure 39: Correlation of experimental CO2 capacity over multiple cycles and model curve fit

Sample	Current	Capacity predicted (wt%)*
C2873-35-31	22.93 (500)	19.29 (1 Yr)
C3022-44-31	14.42 (396)	12.1 (1 Yr)
C2873-29-34	9.22 (500)	9.38 (1 Yr)
ECM224007GC750	20.51(490)	18.54 (1yr)
* Assuming 12 cycles per day (total 4380 cycles)		

Table 4: Predicted CO2 capactiy after multiple cycles based on sorbent composition and TGA experimental data for 500 cycles

Task 3: Powder Production Scale Up

Subtask 3.1: Scale-up Equipment Installation

Several units of large-scale equipment were installed and commissioned for the goal of powder and extrudate scale up.

- **Large scale spray conversion equipment** capable of producing up to 5,000 kg of sorbent powder per year. A new large scale spray processing equipment for scale up of the sorbent production was successfully installed at CSMP during the first quarter of 2005 and tested for reproducibility of the scaled up sorbent production. The evaluation of material performance between the scaled up powder quantities and the previously made sorbent formulations concluded that the sorbent powder characteristics and performance are highly reproducible and the production of the sorbent scaleable.
- **Large scale powder post processing equipment.** As part of the sorbent scale up production effort at CSMP, a large-scale calciner has been installed and commissioned during the second quarter of 2005 for the thermal treatment of the sorbent powder.
- **Large scale mixer and extruder.** The mixing and extrusion equipment were installed and commissioned in the last quarter o 2004 for production of developmental and large extrudate quantities. Large-scale mixer was ordered in the first quarter of 2005.

Subtask 3.2: Produce Catalyst for Reactors

CaO-Based Sorbent Material

Significant effort was focused on optimization of methods for scale up production of sorbent powders and extrudates. 200 kg of sorbent powder have been produced in the third quarter of 2005 for the initial charge of the large-scale adsorption-enhanced reforming reactor.

Sorbent Powder Production: Process Scale Up

The process of large-scale production of CaO-based sorbent powder consists of dissolving the raw materials, performing a chemical reaction and spray conversion of the precursor suspension, followed by post processing/ calcining the resulting powder to convert it to the desired composition. The powder produced by this method can be further processed into pellets to be used in a fixed bed reactor. The final powder consists of calcium oxide and calcium carbonate. The ratio of these components depends upon the extent of calcination. Inert component is also added during the precursor mixing step to produce a composite powder providing higher pellet crush strength and cyclabilty. Prior to producing the sorbent, batch records containing the quantities of raw materials and production parameters were generated and reviewed. The mixing and spray conversion steps were carried out on large-scale spray conversion equipment, and the post-processing of the sprayed powder was done in a rotary kiln. Batch sizes between 5kg and 9kg were produced depending upon shift length and maintenance required. After the material was spray processed the following characterization analyses were performed: BET surface area, average pore volume, average pore diameter, X-Ray Diffraction (XRD), Thermo Gravametric Analysis (TGA), Particle Size Distribution (PSD). These results were compared with previous materials in order to obtain statistical correlations for reproducibility and developmental differences in physical powder properties and to determine the process variance.

Using the data from over 30 batches of sorbent powder, a process control charts were generated for the following powder characteristics: particle size (d_{50}), surface area, pore volume, and pore diameter. Through the use of these control charts, specifications have been put into place – if a batch of material falls outside of the measured characteristic control limits, that powder is set aside and does not continue further on to downstream processing steps. See an example for a control chart on particle size distribution (Figure 40).

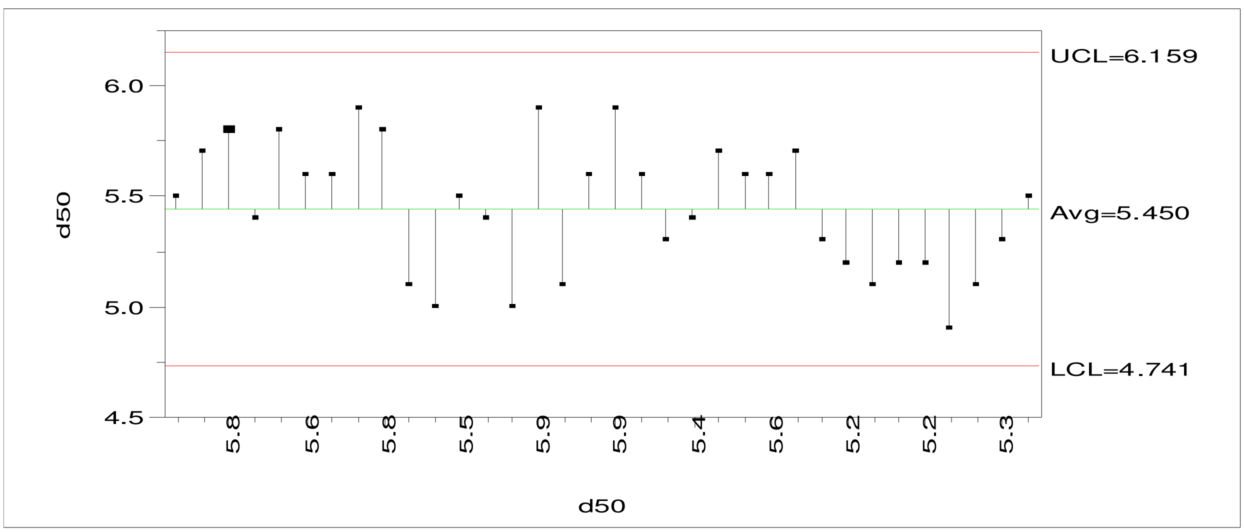


Figure 40: Control chart for particle size measurement - d50 (microns)

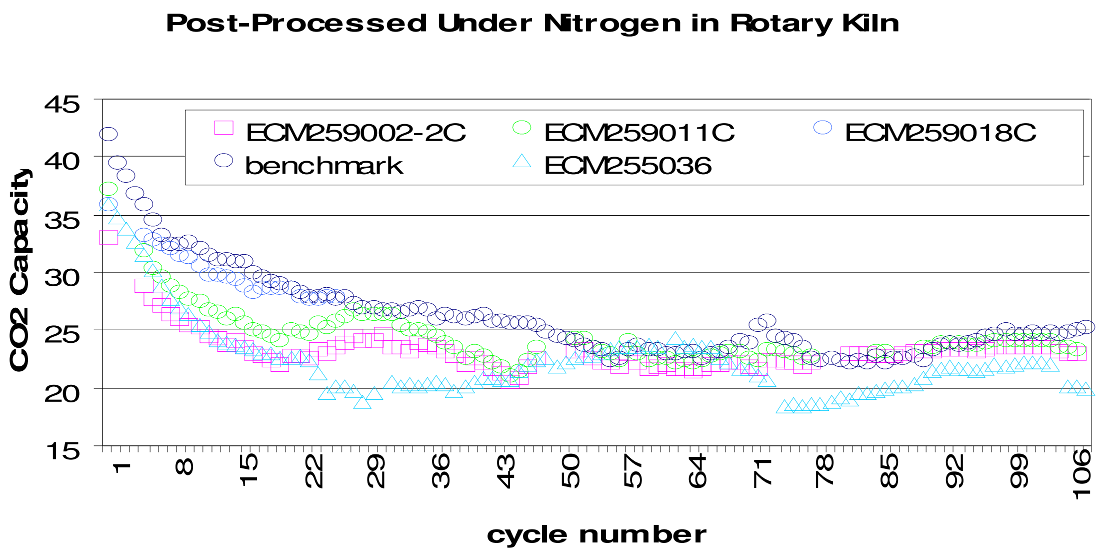


Figure 41: CO2 TGA test data from extrudates post-processed under nitrogen (2C, 11C, 18C), "benchmark" and ECM255036, processed in air

In order to use the spray converted material in its final application, it must undergo a post processing or calcination step. As part of the scale-up effort, post-processing was transitioned from a batch method to a Harper rotary kiln (also referred to as "rotary calciner"). Post-processing was now carried out in a continuous method. This method facilitates higher throughput, as well as results in a more homogenous calcined powder. Several extrudates were made and tested to evaluate the effect of changing the processing gas from air to nitrogen atmosphere during the post processing step for sorbent powders. In-house CO_2 capacity testing showed a slight increase in performance (Figure 41) and AER micro-reactor testing confirmed this finding (Figure 42).

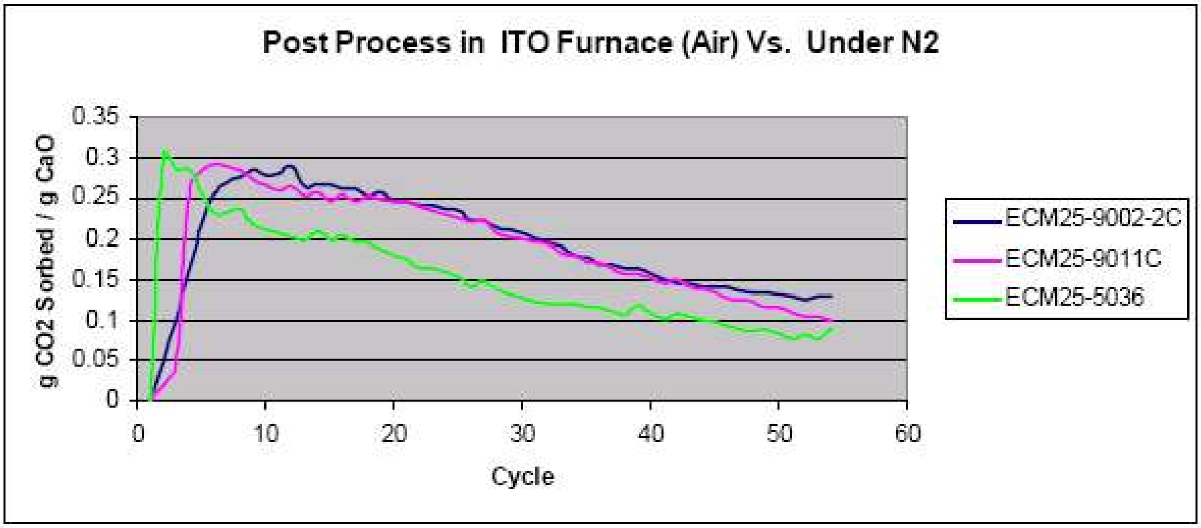


Figure 42: Micro-reactor AER data comparing sample used in 500 cycle reactor demonstration (ECM255036) to two samples post-processed under nitrogen (ECM259002-2C & ECM259011C)

After the material was post processed, the following analyses were performed: BET surface area, Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), Thermo Gravimetric Analysis (TGA), particle size distribution (PSD) and CO_2 capacity testing. The results from these analyses were compared with previous batches in order to obtain statistical correlations for reproducibility and variance in physical powder properties.

Subtask 3.3: Scale-up Optimization for Integrated Materials

Extrudate Production: Process Scale Up

The AER microscale reactor testing identified that the large-scale extrudates (ECM255036) provided by CSMP have lower CO_2 absorption capacity compared to benchmark extrudates. Further analysis of the extrudate characteristics was done to improve the performance of the CSMP extrudates in AER reactor testing.

Investigation of sorbent CO_2-sorption kinetics in the TGA apparatus was undertaken in an attempt to understand why CO_2-sorbent benchmark extrudates outperform in AER reactor testing conditions, those produced at large scale. Specifically, benchmark materials were able to sustain sorption reforming for longer periods of time at high H_2 purity than materials produced with the scale up equipment and approach. Given that these two different types of materials have very similar CO_2 capacities (saturation values), it is believed that the rate at which CO_2 sorption occurs differs for the different materials. Consequently, an effort was undertaken to examine the CO_2-TGA sorption kinetics to:

- (1) Determine if the CO_2-TGA sorption kinetics is a viable model test for predicting AER performance
- (2) Identify the production step(s) that result in poorer AER performance of materials produced with current in-house methods
- (3) Identify sorbent production improvements, which will enhance sorbent AER performance above that achieved by benchmark materials

CO_2-TGA historical data were used to evaluate the kinetics of CO_2 sorption kinetics for various materials. The rate equation was developed assuming CO_2 sorption is 1st order in CO_2 partial pressure and CO_2 sorption is rate limiting.

$$\frac{dM_s}{dt} = k' P_{CO2} (M_T - M_s)$$

where, M_s is the mass (g/g) of CO_2 sorbed, normalized to sample mass (calcined)
k' is the specific sorption rate constant for 600 °C (1/atm/s)
P_{CO2} is the CO_2 partial pressure (atm)
M_T is the max CO_2 sorption capacity (g/g), normalized to sample mass (calcined)
t is time (s)

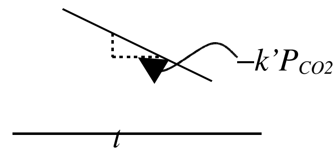
Given that after the initial purging of the CO_2-TGA equipment, P_{CO2} is constant at 1 atm, and M_T is fixed for a given cycle, the rate equation can be solved explicitly.

$$M(t) = M_T [1 - \exp(-k' P_{CO2} t)]$$

Therefore, by plotting $\ln(M_T\text{-}M_s)$ vs. t for a given cycle (for times greater than 800 s, such that P_{CO2} is constant at 1 atm), the specific rate constant, k', can be determined graphically. MT is adjusted slightly from that measured in the CO_2-TGA equipment, as sorption cycles are limited to approximately 4000 s (typically, 92–99% saturation levels are achieved in 4000 s).

e.g.,

$\ln(M_T\text{-}M_s)$



The usefulness of the CO_2-TGA sorption kinetics analysis to predict AER performance is demonstrated graphically below in Figure 43, in which CO_2-TGA sorption kinetics are cross plotted with AER micro-reactor performance.

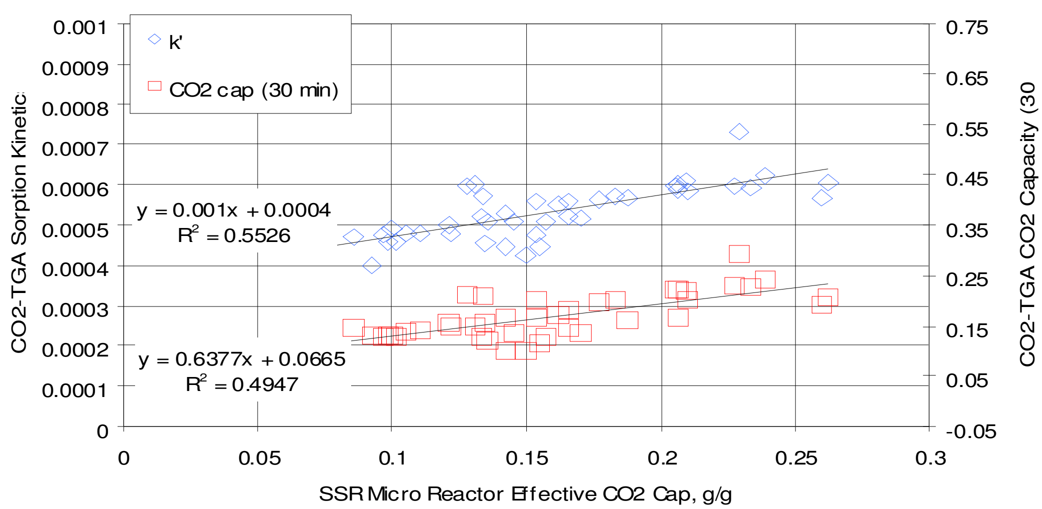


Figure 43: CO2 - TGA sorption kinetics performance cross-plotted with AER micro-reactor performance (functional CO2 capacity in reaction conditions)

From these analyses, the conclusion was made that CO_2-TGA sorption kinetics analysis for extrudates is a reasonable model test for predicting sorbent extrudate performance in AER reactor test conditions and that further improvement of the sorption kinetics of the CSMP extrudates is possible as result of process optimization.

Extrudate Drying and Calcination Study

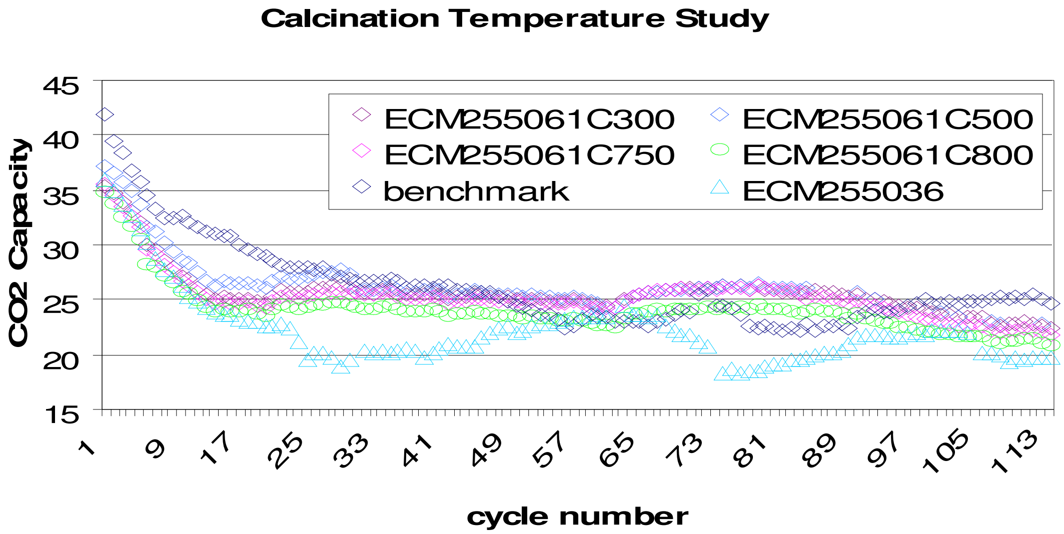


Figure 44: Effect of extrudate calcination temperature on CO2 capacity (as measured by TGA) compared to "benchmark" and ECM255036 (same batch used in 500 cycle test)

A drying and calcination study did evaluate the effect that final extrudate calcination temperature had on extrudate performance. It was found that calcination temperature has limited effect upon the TGA CO_2 capacity of the extrudates (Figure 44). Micro-reactor AER testing, however, demonstrated that final calcination temperature may be an important factor in a sorbent's overall performance. After the sorbent extrudates were dried and calcined at the selected conditions, the following analyses were performed: Thermo Gravimetric Analysis (TGA), crush strength testing, packing density, CO_2 capacity testing, absorption kinetic analysis. Figure 45 compares the absorption kinetics for various extrudates.

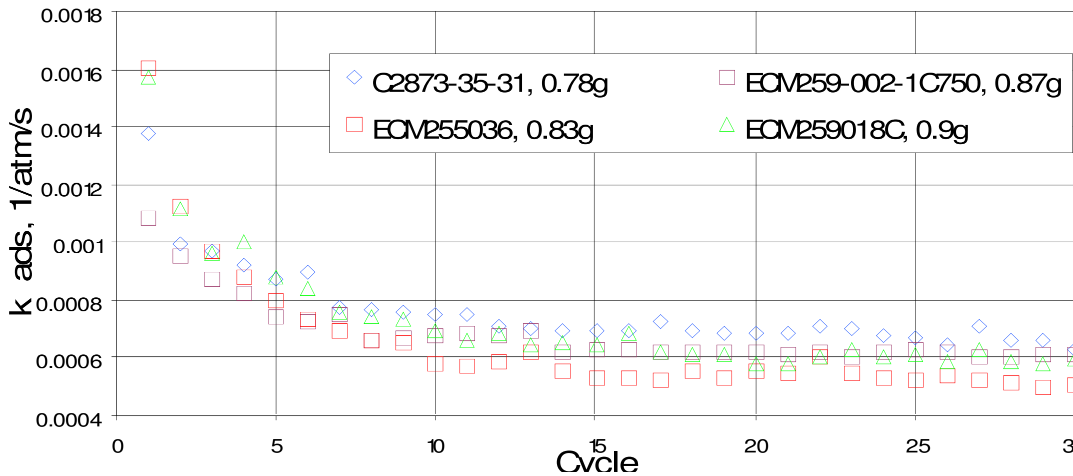


Figure 45: Adsorption kinetics comparison for benchmark extrudate (C2873-35-31), recent CSMP extruadates (post-processed under N2) (ECM259002 & 018C), and extrudate used in 500 cycle demonstration (ECM255036)

Across the board, benchmark extrudates demonstrate faster kinetic rates than the initial CSMP extrudates (ECM255036). However, more recent and optimized CSMP extrudates have improved absorption kinetics and seem to be approaching the benchmark extrudates performance (Figure 45.). Figure 46 illustrates that recent CSMP extrudates are producing promising data in the AER micro-reactor tests. Longer term AER testing, however, is required to determine if the improvements made to CSMP extrudates will translate into increased stability and higher CO_2 capacity at the 500-cycle milestone.

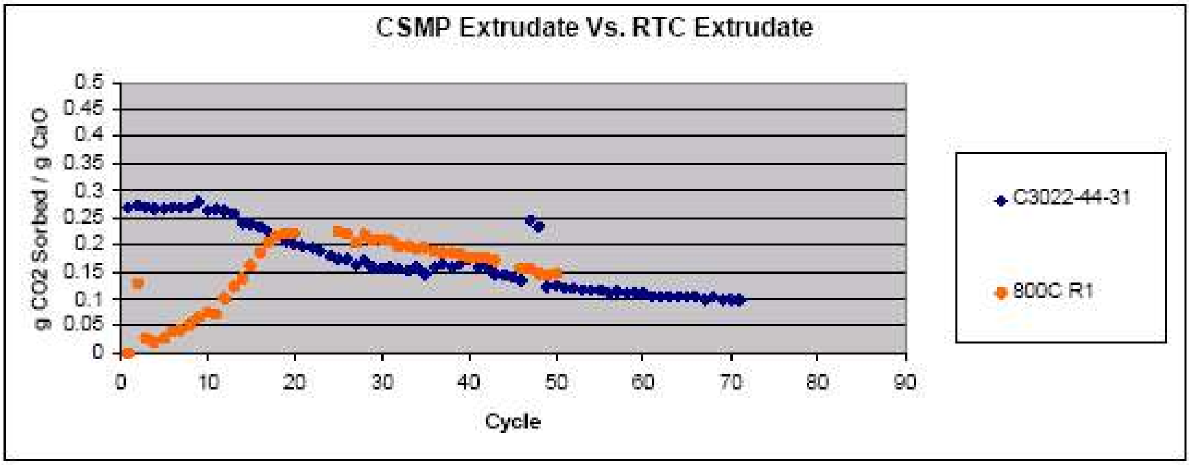


Figure 46: AER micro-reactor data for a recent CSMP extrudate ("800C R1") compared with a benchmark extrudates (C3022-44-3)

Subtask 3.4: Produce Catalyst for Reformer Testing

Task was not attempted due to change in project priorities.

Subtask 3.5: Scale-up of Improved Materials–

2 kg of optimized extrudates was produced and provided to Chevron as a final project deliverable.

Task 4: Reformer Concept Testing

Subtask 4.1: Process Simulation

Extensive modeling and simulation work was performed to support SSR technology development. Detailed description of the work and results are presented in the following sections.

Thermodynamic Studies

Steam methane reforming (SMR) is the most common technology to produce H_2. The process includes steam reforming reaction followed by water-gas-shift (WGS) reaction and PSA purification. The steam reforming reaction is given by the equilibrium reaction:

$$CH_4 + H_2O \rightarrow 3H_2 + CO \qquad \text{(Reaction 1)}$$

Reaction 1 has H =206.2kJ/mol and thus, is strongly endothermic. Effects of reaction temperature and pressure on the CH_4 conversion, at steam-to-carbon (S/C) ratio of 3, are shown in Figure 47. It is evident from the figure that, for a given temperature, methane conversion decreases with increasing pressure.

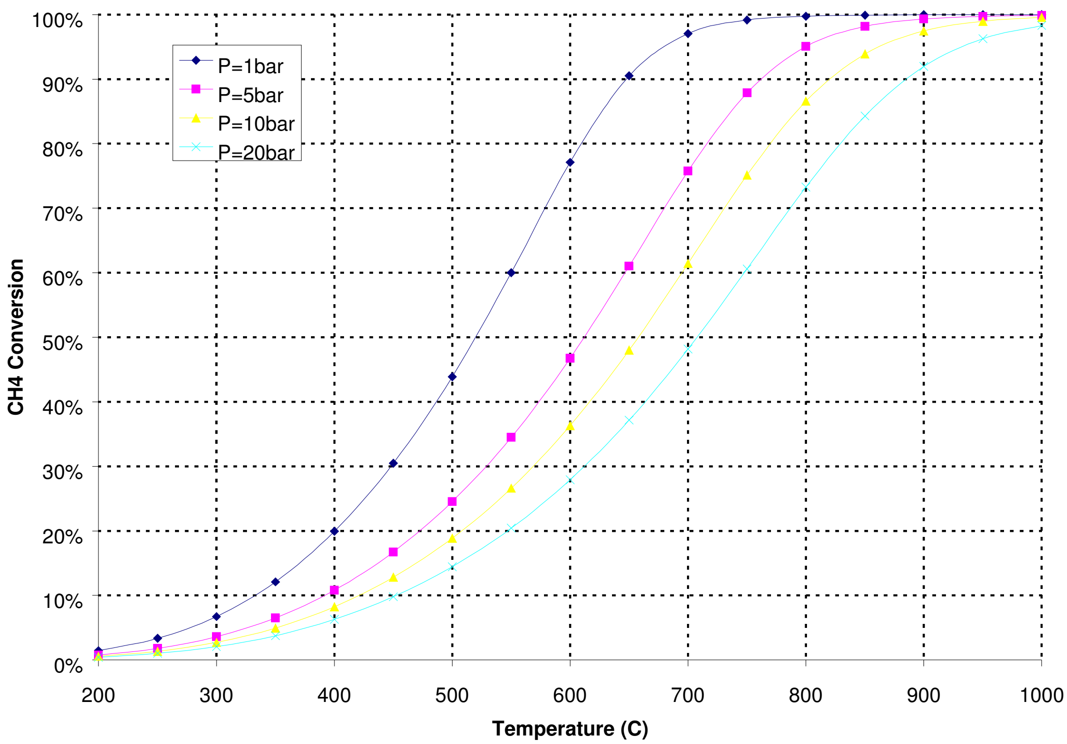


Figure 47: CH4 conversion in SMR as a function of temperature and pressure (S/C=3)

For the industrial SMR application, high pressure operation is preferred to reduce the reactor and piping sizes. High pressure operation also reduces power consumption by compressing higher molecular weight and smaller flow rate of natural gas as opposed to lower molecular weight and larger flow rate of hydrogen. However, as shown in Figure 47, extremely high temperatures are necessary for high CH_4 conversion. For example, the CH_4 conversion is only about 73% at 20 bar and 800°C. Even at lower pressure, the maximum H_2 purity from the SMR is about 77% (dry basis), as shown in Figure 48. Hydrogen purity in the reformate can be increased after the water-gas-shift reactor, but still contains significant CO_2.

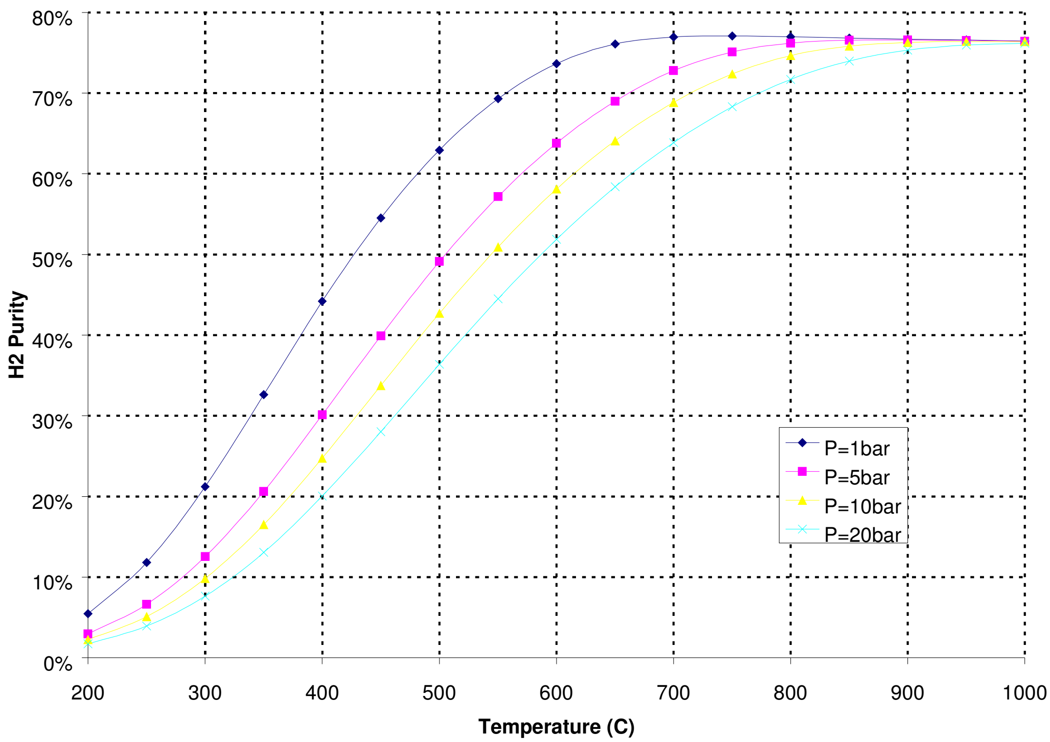


Figure 48: SMR H2 purity as a function of temperature and pressure (S/C=3)

SSR Principles

The equilibrium in Reaction (1) can be driven to the right by *in-situ* CO_2 or H_2 removal. Numerous membrane reactor concepts have been proposed for *in-situ* H_2 separation; however, these reactors are either very expensive (using Pd membrane) or still in early R&D stage (ceramic membrane). The product H_2 in a membrane reaction is in the permeate side and hence, at lower pressure. This is undesirable because of the power required to recompress H_2.

Another approach to drive the SMR equilibrium is by CO_2 removal. This can be achieved by using CO_2 adsorbents in the SMR. This process is also known as adsorption-enhanced-reforming (AER) or single-step reforming (SSR). As the name signifies, high hydrogen purity can be achieved in a single step instead of a multi-step process involving steam reforming, water-gas shift and selective oxidation steps. The SSR reactions include:

$$CH_4 + H_2O \rightarrow 3H_2 + CO \qquad \text{(Reaction 1)}$$
$$CO + H_2O \rightarrow H_2 + CO_2 \qquad \text{(Reaction 2)}$$
$$CaO + CO_2 \rightarrow CaCO_3 \qquad \text{(Reaction 3)}$$

Because of the Reaction 3, equilibrium in Reaction 1 and Reaction 2 are driven to the right side. Figure 49 shows the comparison of equilibrium CH_4 conversion (S/C = 3 and 1 bar) of SSR with SMR, at different temperatures.

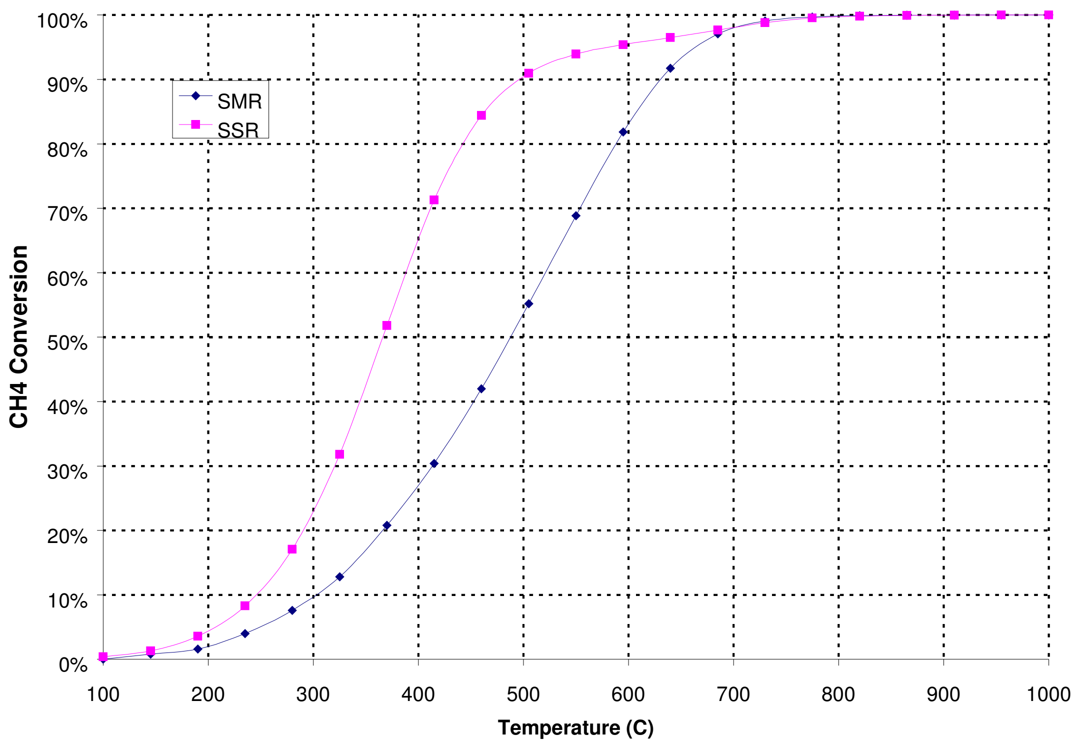


Figure 49: Comparison of CH4 conversion - SSR vs. SMR (S/C=3 and P=1bar)

As shown in Figure 49, SSR CH_4 conversion is significantly higher than that of SMR in the temperature range 450°C to 600°C. Above 700°C, SSR CH_4 conversion is same as that of SMR because the CO_2 adsorption is not favored at higher temperatures. Figure 50 shows the equilibrium gas compositions (dry basis) as a function of temperature.

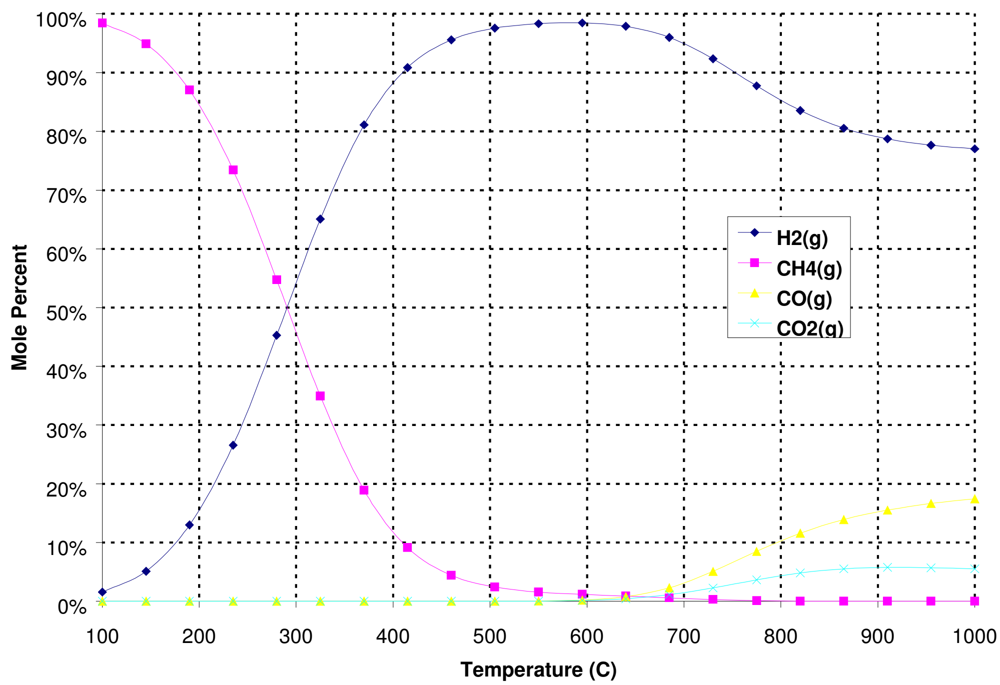


Figure 50: SSR equilibrim gas composition (dry basis) (S/C=3 and P=1bar)

As shown in the above figure, H_2 concentration can get around 98% in the temperature range 500°C to 650°C in single-step reformer (SSR). Above 650°C, the CO_2 adsorption kinetics decreases and thus, both CO and CO_2 concentrations start to increase. SSR equilibrium gas concentrations approach SMR composition at temperatures above 650°C.

Non-Equilibrium SSR thermodynamics

As explained earlier, CH_4 conversion in SSR is higher because of the CO_2 removal from the gas phase to the solid phase adsorbents. CO_2 equilibrium pressure as a function of temperatures is shown in Figure 51.

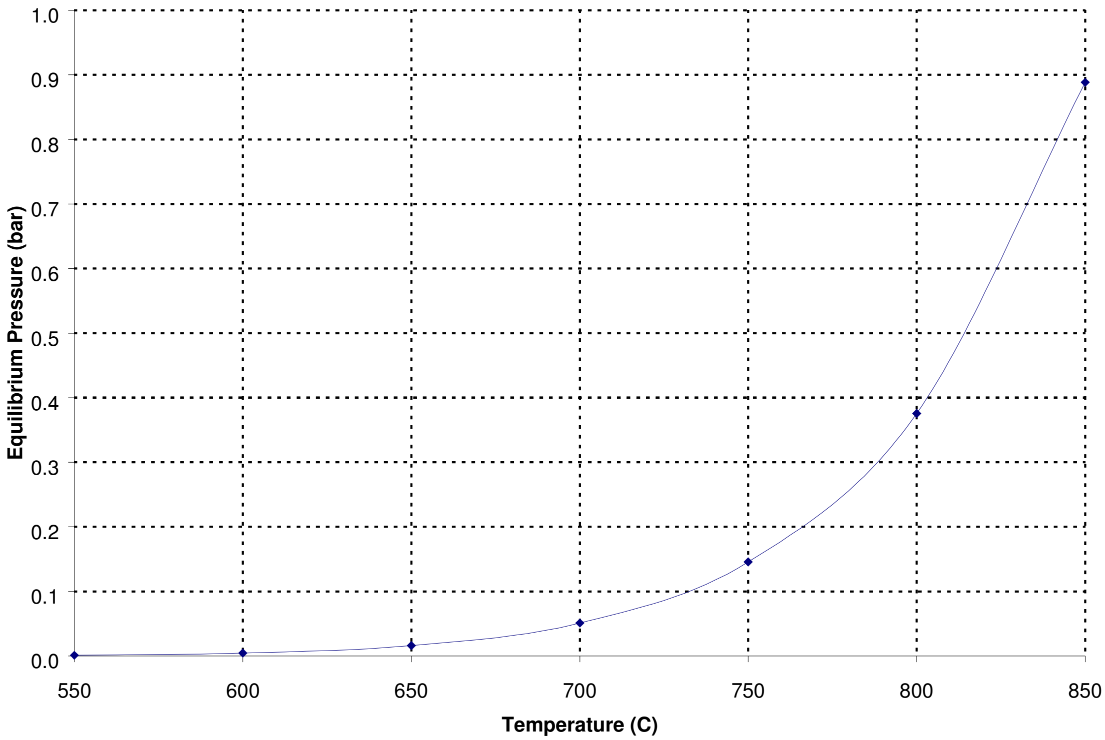


Figure 51: CO2 equilibrium pressure as a function of temperature

At a given temperature, CO_2 absorption will be favored when the CO_2 partial pressure in the gas phase is higher than the equilibrium pressure. Under favorable conditions, presence of CO_2 adsorbents in a SMR reaction will drive the SMR equilibrium to increase the CH_4 and CO conversion. On the other hand, for a given temperature, regeneration of adsorbent is favored when the CO_2 partial pressure in the gas phase is lower than the equilibrium pressure.

It is well known that the steam reforming and the shift reaction (Reaction 1 and 2) are the equilibrium driven; thus, the reforming process can be modeled as an equilibrium reactor. CO_2 adsorption or desorption reactions are driven by difference between CO_2 partial pressure in the gas phase and CO_2 equilibrium pressure. An overall equilibrium reactor assumes that both the SMR reaction and the CO_2 adsorption are in the equilibrium, which means that the gas phase CO_2 partial pressure is equal to the adsorbent CO_2 equilibrium pressure. While it is possible to reach equilibrium in an ideal reactor, in practice it is likely that the reactor will be at non-equilibrium conditions.

Thus, it is necessary to study non-equilibrium CO_2 adsorption. This was modeled by introducing a CO_2 removal factor, which could range from 0 to the equilibrium value. When CO_2 removal factor is 0, the overall reaction will be pure steam reforming (SMR) and typically, is the case when sorbent material reached their full CO_2 absorption capacity. When CO_2 removal factor is at its equilibrium value, the gas phase CO_2 partial pressure is the same as the CO_2 equilibrium pressure, and this corresponds to theoretical maximum CO_2 removal condition. In the practical operation, CO_2 adsorption factor will lie between these two extreme cases and can be obtained from reactor testing.

We assumed the SSR reforming feed includes *m* moles of methane, steam to carbon ratio of S/C; CH_4 conversion in Reaction 1 is x; CO conversion in Reaction 2 is y; and CO_2 adsorption factor in Reaction 3 is z. After reactions (1-3), the gas phase flow rates can be expressed as:

$F_{CH4} = m(1 - x);$
$F_{CO} = m(x - y);$
$F_{H2} = 3mx + my;$
$F_{CO2} = my(1-z);$
$F_{H2O} = m(S/C) – mx – my;$

The species molar fractions were obtained by dividing the above flow rates by the sum of all species flow rates. The gas phase equilibrium equations can be written as:

$$k_1 = \frac{P^2[CO][H_2]^3}{[CH_4][H_2O]}$$
$$k_2 = \frac{[CO_2][H_2]}{[CO][H_2O]}$$

where k_1 and k_2 are equilibrium constants of Reaction 1 and Reaction 2, respectively. By plugging the CO_2 adsorption factor, obtained from testing or an assumed value, the above two equations can be solved to find the species flow rate and fractions in the reformate.

Figure 52 shows the effect of CO_2 removal factor on the CH_4 conversion. Five cases are presented; CO_2 removal factors of 0%, 50%, 90%, 95% and 99%. It should be noted that some CO_2 removal factors are not practical because of equilibrium limitation. For example, at 700°C and 1 bar, the equilibrium (maximum) CO_2 removal factor is only 50%.

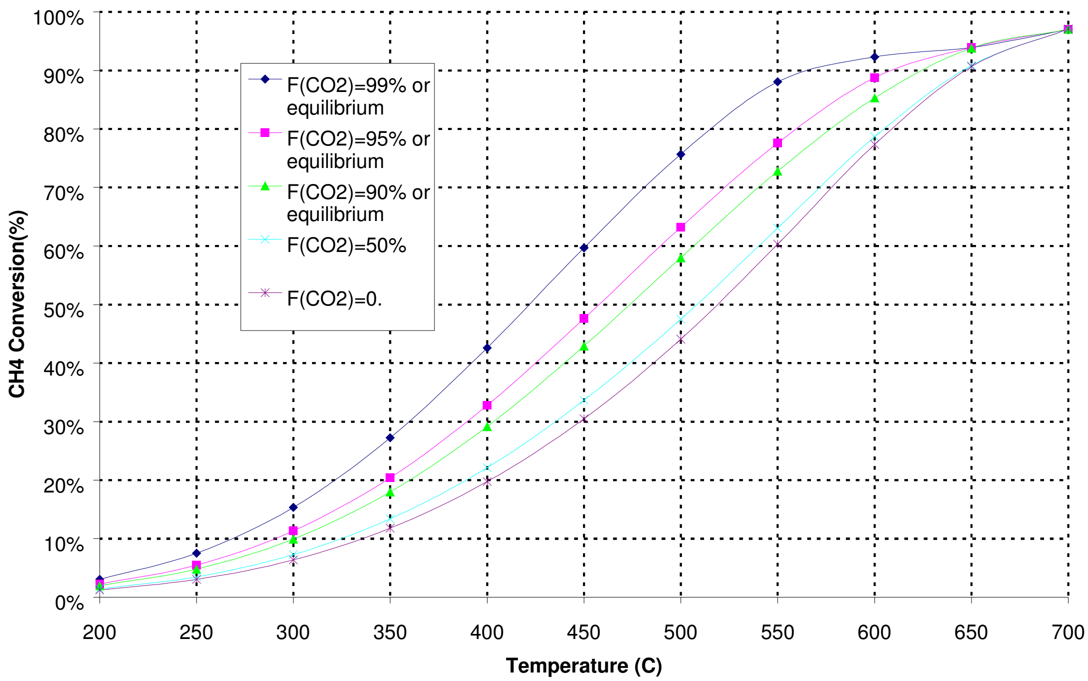


Figure 52: Effect of CO2 removal factor on the SSR CH4 conversion (S/C=3 and P=1.013bar)

As can be seen in Figure 52, CO_2 removal factor has major impact on CH_4 conversion. H_2 purity also increases with CO_2 removal factor. Figure 53 shows the effect of CO_2 removal factor on H_2 purity. As shown in Figure 53, H_2 purity can reach about 90% when 90% CO_2 is adsorbed.

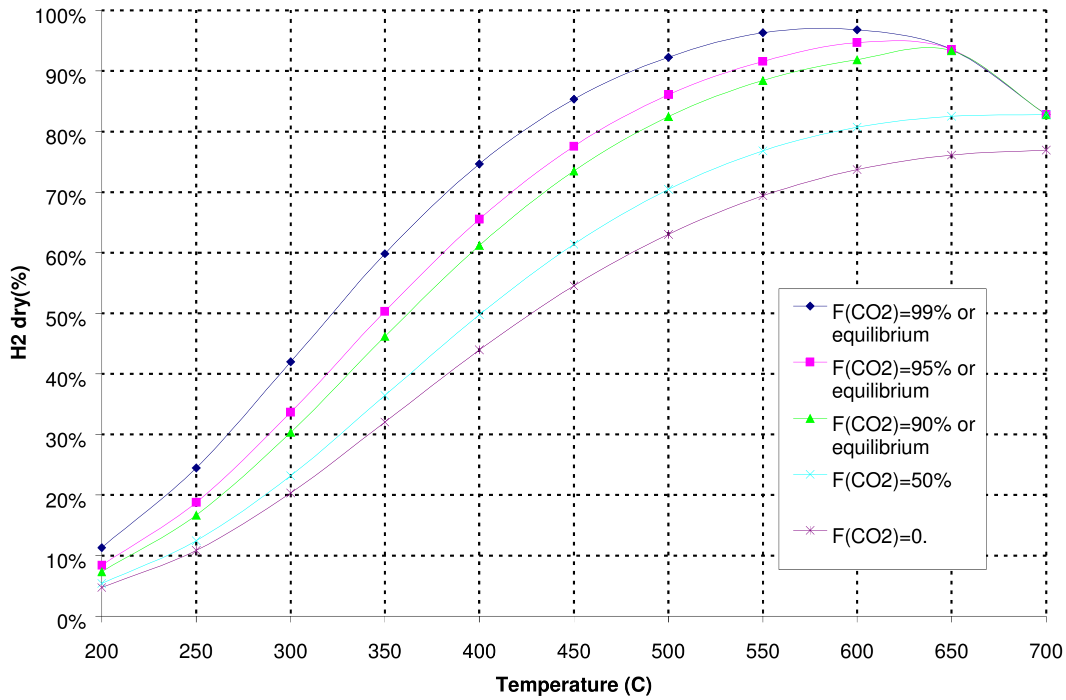


Figure 53: Effect of CO_2 removal factor on H_2 concentration (S/C=3 and P=1.013bar)

For a given system pressure, an optimum reforming temperature exists to maximize hydrogen purity after the methanator. The effect of system pressure on optimum reforming temperature, and corresponding hydrogen purity and methane conversion are shown in Figure 54.

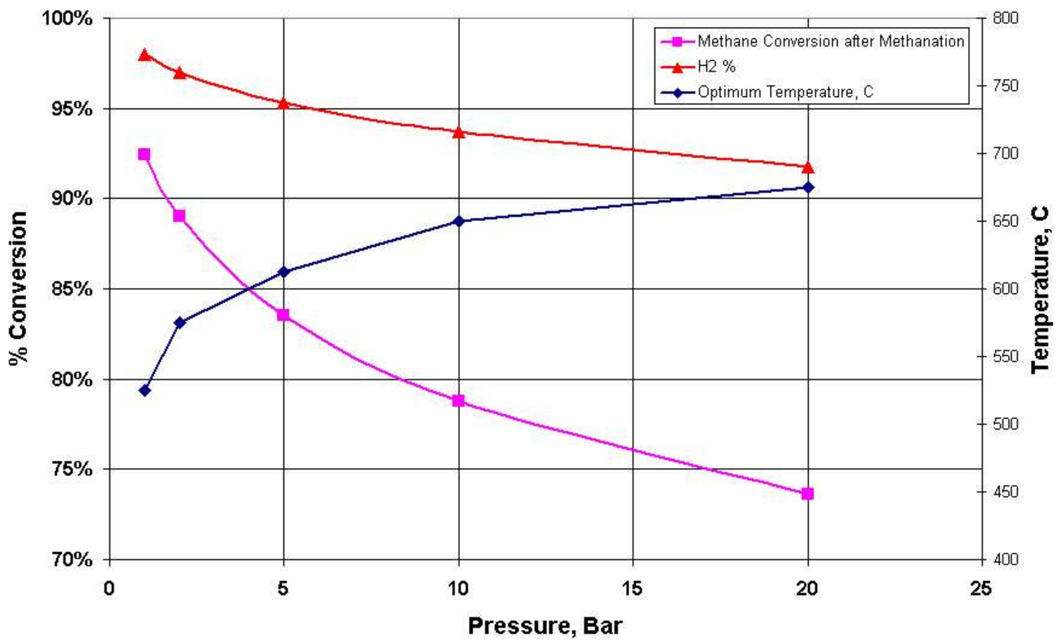


Figure 54: Effect pressure on SSR at optimum temperature of operation (S/C=3)

Figure 55 shows methane conversion in SSR, at S/C of 3 and temperature of 600°C, as a function of pressure. Higher pressure requires higher CO_2 removal factor to reach the equilibrium. This is because, for a given temperature, equilibrium CO_2 pressure is constant. So the equilibrium mole fraction of CO_2 decreases with increasing pressure and hence, more CO_2 has to be removed to obtain this equilibrium. Also higher the SSR reforming pressure, lower the H_2 concentration. Figure 56 shows the effect of CO_2 removal factor on H_2 concentration at different pressures. The figure illustrates that it is better to operate SSR at low pressures.

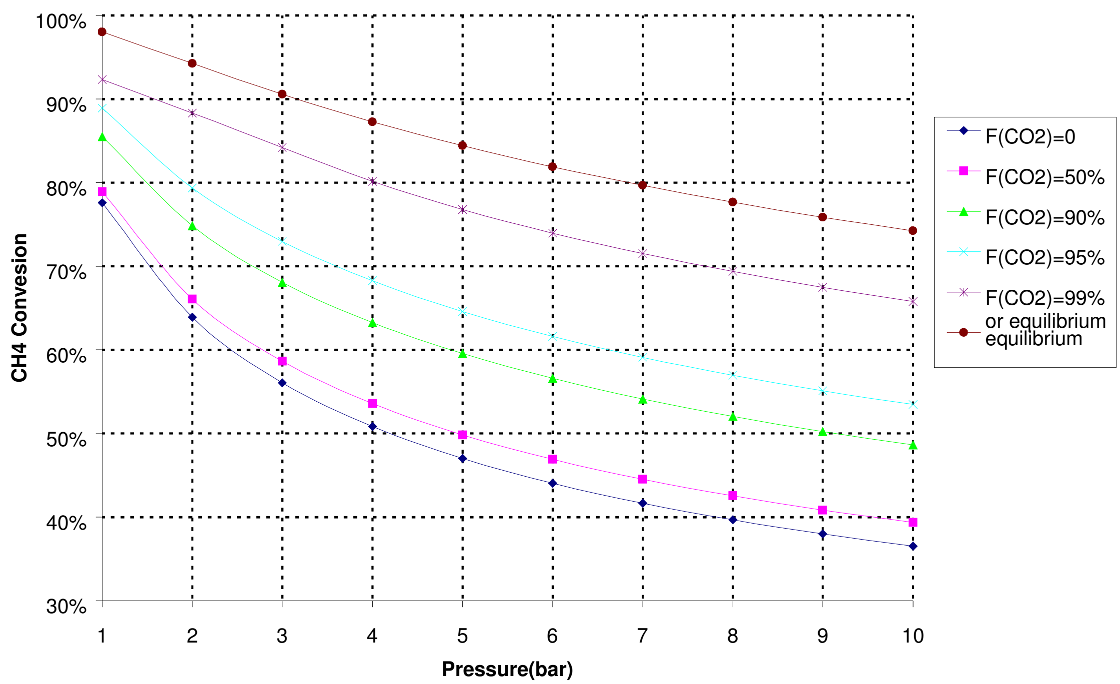


Figure 55: Effect of CO_2 removal factor on the SSR CH_4 conversion (S/C=3, T=600°C)

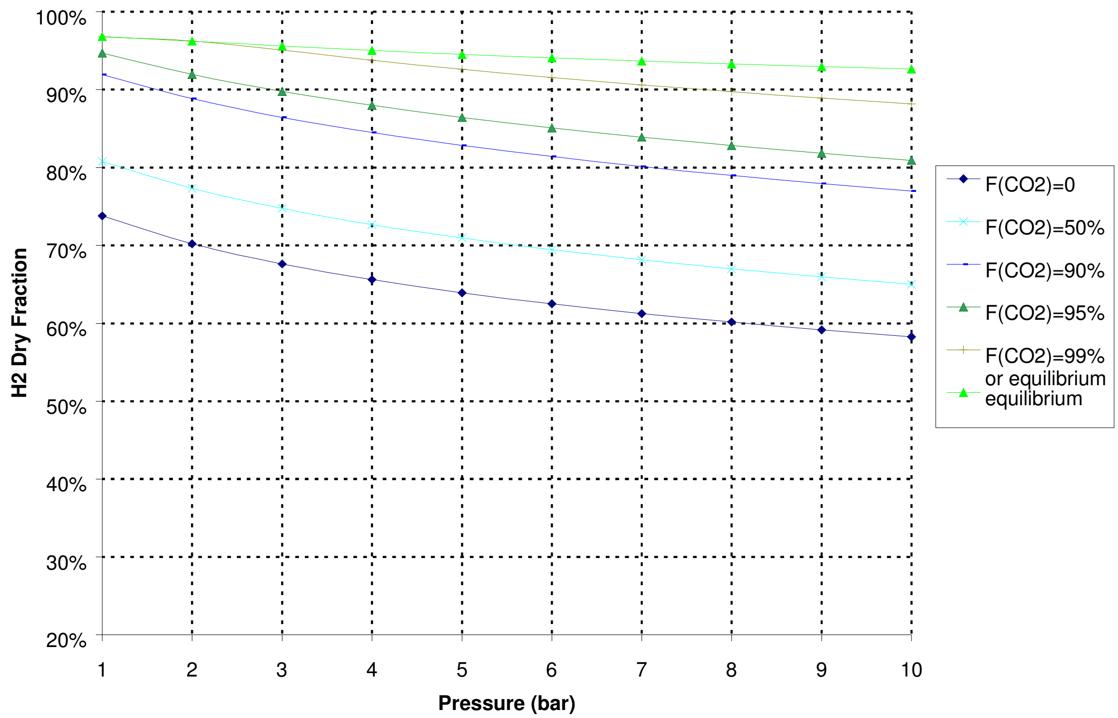


Figure 56: Effect of CO2 removal factor on H2 concentration (S/C=3, T=600°C)

SSR Reactor Dynamic Modeling

The reforming and regeneration reactions in a fixed-bed SSR reactor are dynamic processes. Steam-methane reforming is an endothermic process, and shift reaction is slightly exothermic; while CO_2 adsorption is exothermic and CO_2 desorption is endothermic. The extent of these reactions will affect the bed temperature and vice-versa. The reactor also has heat and mass transfer between the gas phase and the packed bed solid phase of adsorbents and catalysts.

Several questions arise in designing for SSR process, such as

- During the SMR and the carbonation process, how long can the hydrogen concentration stay above the desired value?
- How long will be the regeneration process?
- What are the optimum inlet conditions for the SMR and carbonation, such as temperature, pressure, S/C ratio?
- What regeneration method should be used, e.g. high temperature steam or combustion gas? What flow rate and temperature should be?
- Which reactor design scheme is better, the segmented mixed bed or a single bed?
- Which thermal management scheme is better?

- How these design schemes affect the system efficiency?

Since the SSR process is inherently dynamic, we used dynamic modeling to address all the above questions.

Theoretical Model

We developed a non-isothermal, non-adiabatic, and non-isobaric theoretical model for SSR process. It was used to describe all processes that could happen in the reactor, including steam–methane reforming (SMR), adsorption-enhanced reforming (AER), combustion gas and steam regeneration, in-situ catalyst combustion regeneration, steam or air cooling and purge processes. The following were the assumptions/basis for the model:

(1) The gas phase flow was represented by a plug-flow model. Change of flow due to sorption and reactions, as determined by the overall material balance, was incorporated in the model. The gas thermal properties were used from the RKS-BM model in Aspen® Properties.

(2) The sorption-bed was described by an energy balance equation. Thermal conduction, convection between the gas phase and the solid phase, and the CO_2 adsorption and desorption heat were included in the energy balance equation.

(3) Convection heat transfer exists between the gas phase and the solid phase.

(4) CO_2 convection mass transfer exists between the gas phase and the solid phase.

(5) Seven components, CH_4, H_2, CO_2, CO, O_2, N_2 and H_2O, were assumed to be present in the model. Same model was used to simulate various processes including reforming, regeneration and combustion and cooling steps.

From the above assumptions, we derived the following governing equations. The first governing equation was the gas phase overall mass balance with the assumption of no gas holdup:

$$\frac{\partial F}{\partial x} = R_{CO_2} \quad (1)$$

Where: F - gas phase mass flux.
R_{CO2} - CO_2 adsorption and desorption rates.

The gas phase species balance was written as

$$\frac{\partial C_i}{\partial t} = -\frac{\partial \left(vC_i \right)}{\partial x} - \sum R_i \quad (2)$$

Where:
I - species including CH_4, H_2, CO_2, CO, O_2, N_2 and H_2O
R_i - chemical reaction including adsorption and desorption
 - porosity of the packed bed
v - velocity
C - molar concentration of gas species
t - time
x - reactor bed length.

The gas phase energy balance equation was expressed as

$$\frac{\partial E}{\partial t} = -\frac{\partial \left(FH \right)}{\partial x} + \dot{Q}_R - Q_s - Q_{HE} \quad (3)$$

Where:
E - internal energy
H - enthalpy
Q_R - reaction heat
Q_s - heat transferred between the gas phase and the solid phase

Q_{HE} - all heat transferred between the gas and the environment, such as the heat loss from reactor vessel or heat exchange between the gas and heat exchangers if present

The solid phase energy balance equation was

$$C_P \frac{\partial T_s}{\partial t} = \quad (4)$$

Where: Q_{ad} - CO_2 adsorption/desorption heat, it has positive value when CO_2 is adsorbed and negative value when CO_2 is desorbed

T_s - bed temperature

- bed density

C_P - bed specific heat;

$_{eff}$ - bed thermal conductivity.

The heat transfer between the gas phase and the solid phase was

$$Q_s = hA\left(T - T_s\right) \quad (5)$$

Where: h - heat transfer coefficient in the packed bed

A - specific surface area (m^2/m^3)

Reaction Kinetics Model

The three main chemical reactions in the steam-methane reforming process were described by the following equations ([Xu and Froment 1989]):

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2$$

The reaction kinetic model of Xu and Froment was written as

$$R_I = \frac{k_1}{P_{H_2}^{2.5}} \left(P_{CH_4} P_{H_2O} - \frac{P_{H_2}^3 P_{CO}}{K_I} \right) / \left(DEN \right)^2$$

$$R_{II} = \frac{k_2}{P_{H_2}^{3.5}} \left(P_{CH_4} P_{H_2O}^2 - \frac{P_{H_2}^4 P_{CO_2}}{K_{II}} \right) / \left(DEN \right)^2$$

$$R_{III} = \frac{k_3}{P_{H_2}} \left(P_{CO} P_{H_2O} - \frac{P_{H_2} P_{CO_2}}{K_{III}} \right) / \left(DEN \right)^2$$

$$DEN = 1 + K_{CO} P_{CO} + K_{H_2} P_{H_2} + K_{CH_4} P_{CH_4} + K_{H_2O} P_{H_2O} ¿ P_{H_2}$$

where, k_1, k_2, k_3 - rate constants of reactions
K_I, K_{II} and K_{III} - equilibrium constants;
K_i - adsorption constant for component i.

CO2 Carbonation and calcinations reactions were

$$\mathrm{CaO} + \mathrm{CO_2} \rightarrow \mathrm{CaCO_3}$$
$$\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2}$$

The carbonation kinematics was described using the following equation (Garcia-Labiano et al.)

$$(r)_C = k_C A (1 - \quad) \left(1 - \frac{P_{CO_2}}{P_{eq}} \right)$$

$$P_{eq} = 4.137 \times 10^{12} \exp\left(-\frac{20474}{T} \right) .$$

Where: k_C - chemical reaction rate constant.
\- fraction of active sites;
P_{eq} - equilibrium CO_2 partial pressure;

Numerical Method

The above governing equations were solved using Aspen© Custom Modeler (ACM) as a platform. The Finite difference method was used to discretize the differential governing equations. The integration and nonlinear solver in ACM solves the governing equations by the Variable Step Implicit Euler and the Newton iteration method respectively.

The numerical method was verified by total mass balance, gas phase energy balance, solid phase energy balance, and gas and solid system energy balance. We also verified that number of nodes does not affect the simulation results.

Comparison of Model Results with Test Data

The theoretical model was verified with experimental tests. Figure 57 shows an example of model data compared to the test data. In this example, the mixture of N_2 and CO_2 was used to test the carbonation kinetics, and N_2 was used for the regeneration sweeping gas. The purpose of using N_2 and CO_2 mixture was to verify the CO_2 adsorption kinetics in a well controlled environment.

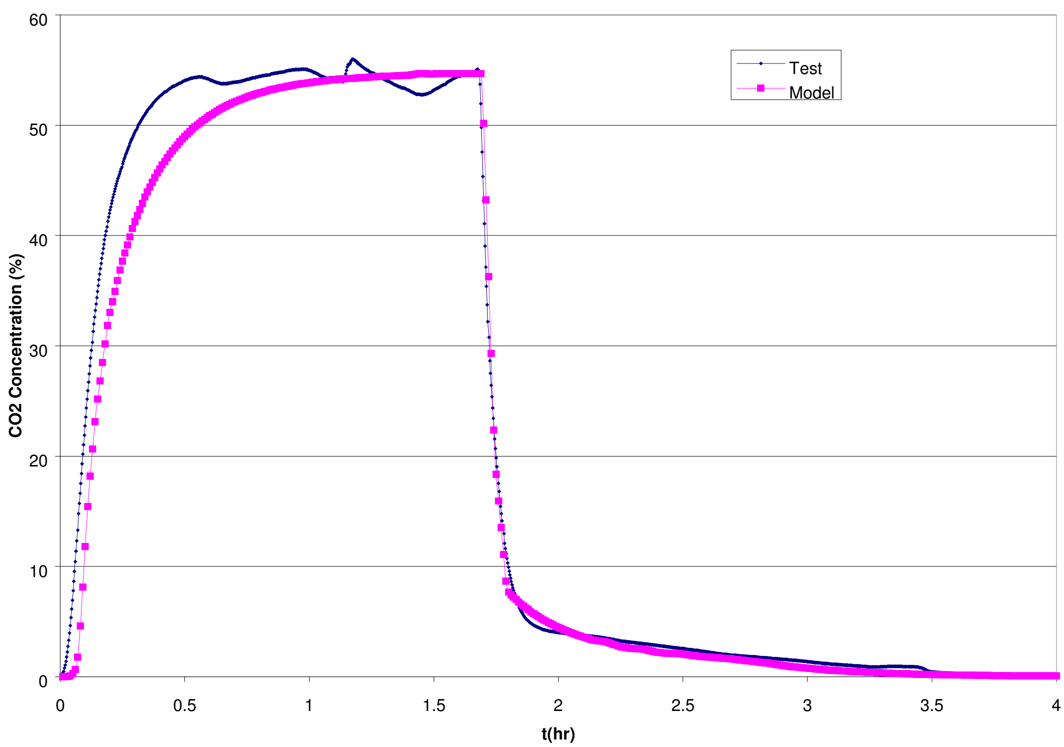


Figure 57: Comparison of model results with test data

As shown in the Figure 57, CO_2 and N_2 mixture was introduced into a microreactor for the CO_2 adsorption test. Initially, CO_2 concentration in the exhaust gas was low due to absorption. With time, CaO gets converted to $CaCO_3$ and the CO_2 absorption decreases. So the CO_2 concentration increases in the exhaust gas. In this experiment, after 1 h, the exhaust gas CO_2 concentration was very close to that of the inlet mixture indicating absence of CO_2 absorption. After 1.68 h, the inlet mixture was switched to pure N_2 and the microreactor temperature was ramped to 850°C. The sorbent materials started regeneration by releasing CO_2. The CO_2 concentration keeps decreasing until almost all CO_2 is desorbed. The experimental conditions were modeled and the model results agree well with the test data, as shown in Figure 57, validating the model and CO_2 adsorption/desorption kinetics.

SSR Reforming Reactor- Base Case Simulation Results

Our base case included three processes: reforming, regeneration and cooling. We assumed the reforming and regeneration will take 1hr each, and the cooling will take 0.5hr. The base case reactor operating conditions are listed in Table 5.

Parameters	Units	**Values**
Reactor Length	m	**0.75**
Reactor Diameter	m	**0.25**
Catalyst and adsorbent bulk density	kg/m^3	**700**
Catalyst and adsorbent specific area	m^2/m^3	**944**
Catalyst and adsorbent specific heat	kJ/kg/K	**1.028**
Catalyst and adsorbent thermal conductivity	W/m/K	**10**
Catalyst and adsorbent void fraction		**0.434**
Reforming feed (3:1 Steam to Carbon) flow rate	kmol/hr	**0.2688**
Reforming feed (3:1 Steam to Carbon) temperature	°C	**600**
Reforming time	hr	**1**
Regeneration flow rate	kmol/hr	**2.948**
Regeneration flow temperature	°C	**850**
Regeneration time	hr	**1**
Cooling flow rate (air)	kmol/hr	**2.948**

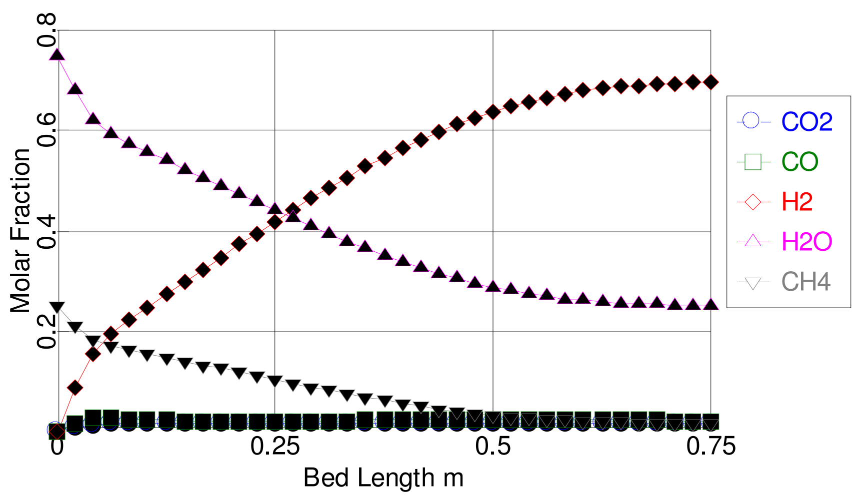
Cooling flow temperature	°C	**25**
Cooling time	hr	**0.5**

Table 5: Base case reactor and flow conditions

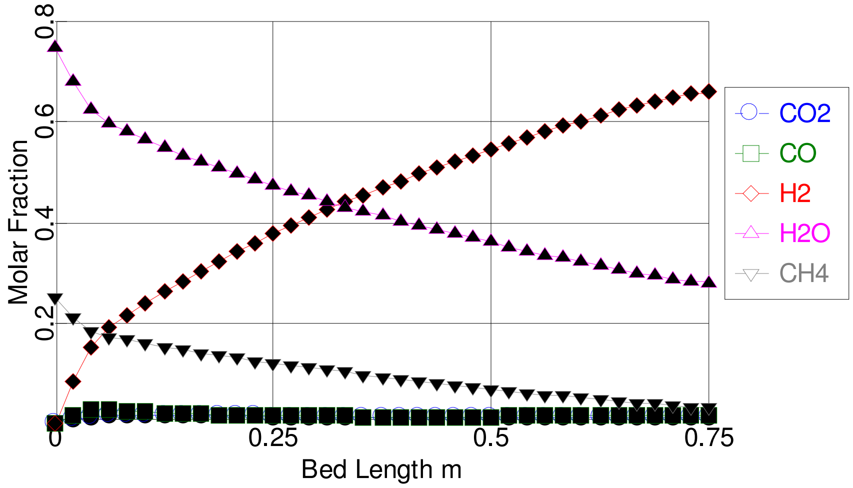
Since we used a distributed dynamic model, our model can predict the operating parameter profiles along the reactor and their changes with time.

Reforming Results

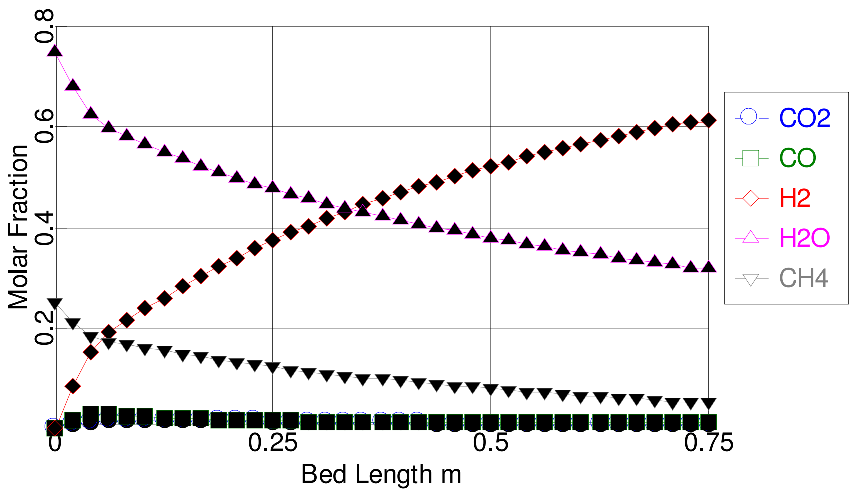
Figure 58 (a-d) shows the reforming gas molar fraction profile at time t=0.25hr, t=0.50hr, t=0.75hr and t=1hr.



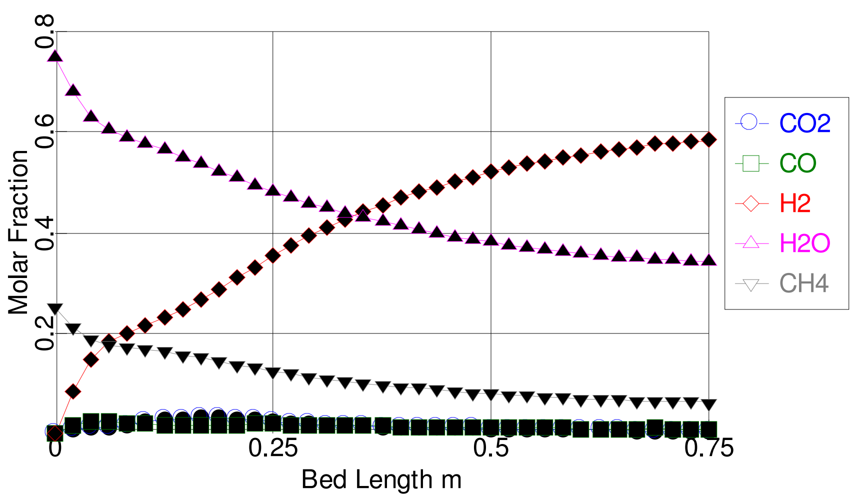
(a) t=0.25hr



(b) t=0.50hr



(c) t=0.75hr



(d) t=1hr

Figure 58: Reforming gas molar fraction at different times

As shown in Figure 58, at each time period, CH_4 and H_2O concentrations decrease and H_2, CO and CO_2 concentrations increase along the reactor. The CO and CO_2 concentrations are relatively low compared to a SMR process due to CO_2 adsorption. Figure 59 shows the change in reforming outlet gas molar fraction with time. It should be noted that the gas molar fractions presented in the figure are based on "wet" conditions, i.e. include steam in the calculation.

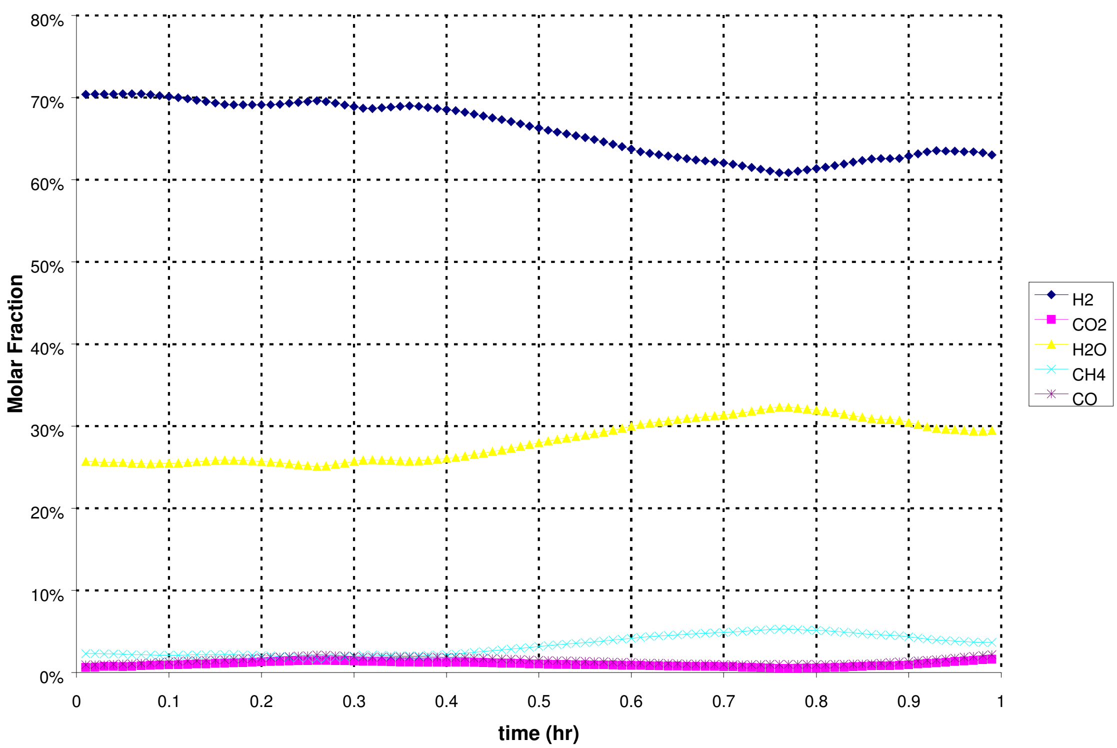


Figure 59: Reformate gas molar fraction (wet basis) with time

As evident from Figure 59, H_2 molar fraction is high and stable initially but decreases with time. On the other hand, CH_4 concentration increases with time; while CO_2 and CO molar fractions are relatively low. The decrease in H_2 concentration with time is due to lower CH_4 conversion, which in turn is driven by CO_2 absorption.

Figure 60 shows a typical reforming gas and solid temperature profile in the reactor at t=0.5hr. The gas temperature drops rapidly at the inlet of the reactor, which is due to fast and highly endothermic steam reforming reaction. After the initial temperature drop, the gas temperature increases due to the heat release from CO_2 absorption in the packed bed. The heat released from CO2 absorption provides most of the heat required by the endothermic steam reforming and the overall process is slightly endothermic. It can be seen that the gas temperature is very close to the bed temperature after the reactor entrance. This is attributed to the assumption of good heat exchange between the gas and the bed due to high surface area to volume ratio in the packed bed.

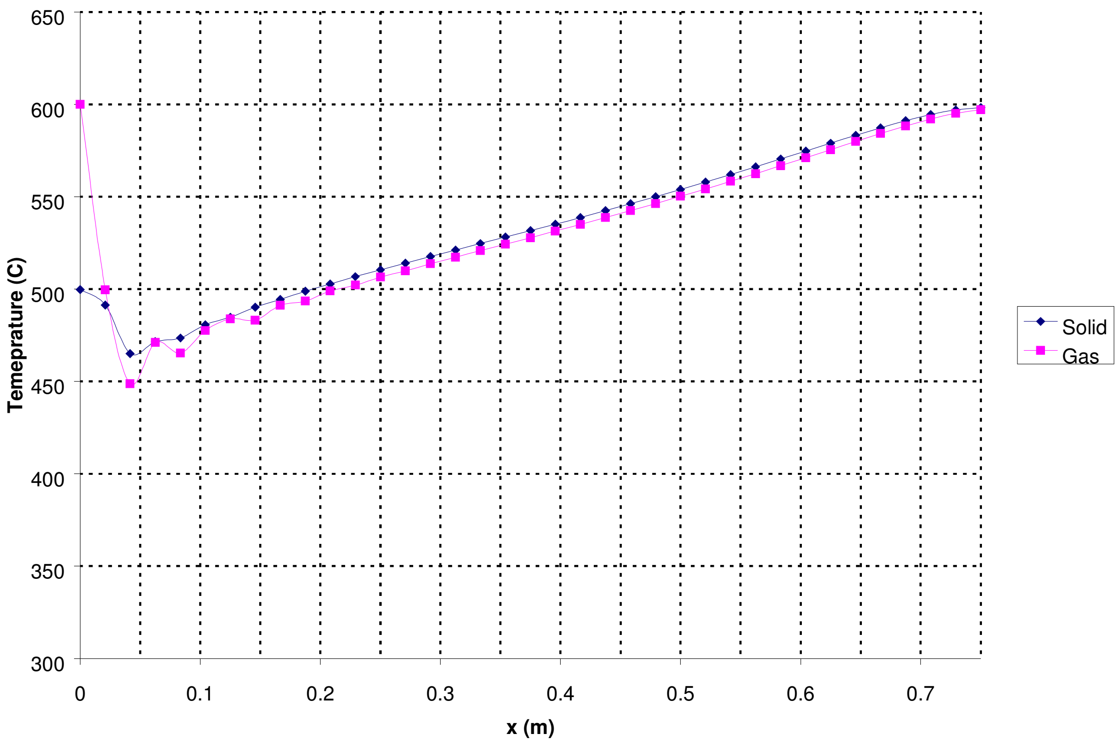


Figure 60: Gas and solid temperature profile in the SSR reforming reactor (t=0.15hr)

Figure 61 shows temperature-time profile at various positions along the length of the bed. We used 36 nodes in the simulation, and T(1) represents the reactor inlet, T(36) represents the reactor outlet and others are linearly distributed in the reactor (number represents the node number).

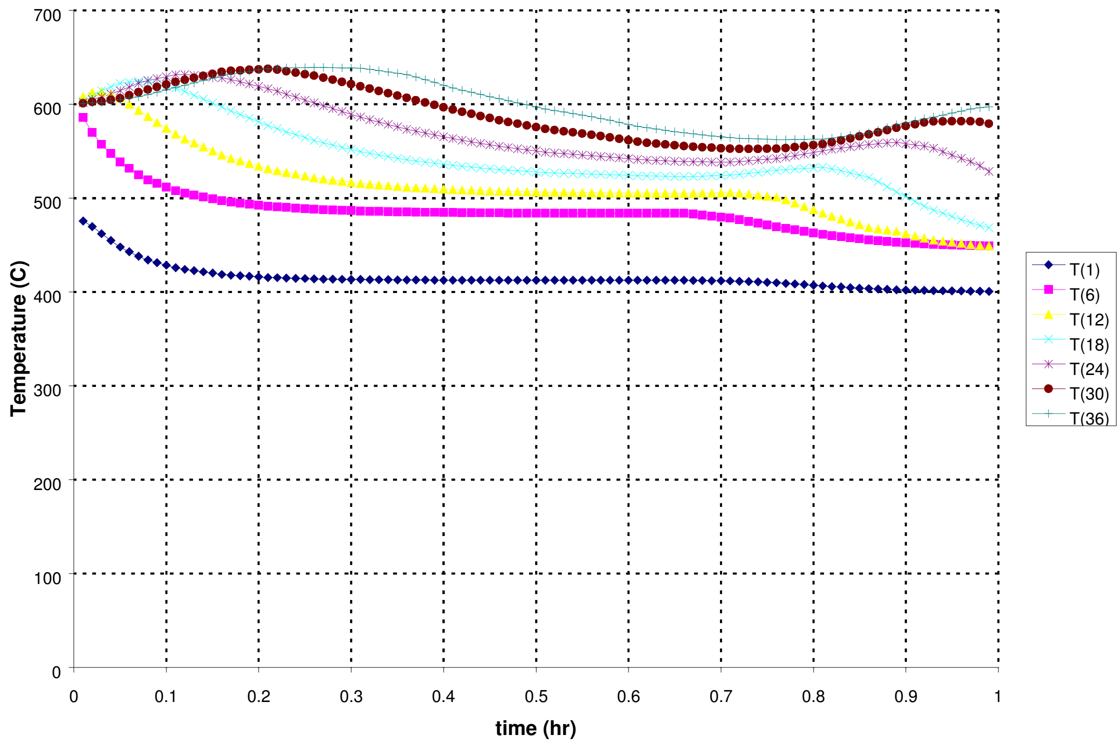


Figure 61: Gas temperature profiles during the reforming process

Reactor inlet temperature, measured by T(1), shows a slight increase and then decreases to SMR equilibrium temperature. This is attributed to dominant steam reforming reaction at the inlet due to material reaching its capacity quickly. On the other hand, the temperature at the end of the packed bed increases early in the reforming step due to a dominant CO_2 adsorption. However, the temperatures eventually will drop due to decrease in absorption capacity of the sorbent. So, the overall bed temperature will decrease with time. The decreasing bed temperature will lower the equilibrium constant for steam reforming as steam reforming is strongly dependent on temperature. This, in turn, will reduce hydrogen concentration and decrease methane conversion.

Figure 62 shows the CaO and $CaCO_3$ molar fraction profile in the reactor at the end of reforming step. The CaO molar fraction at the front part of reactor is zero indicating complete utilization of the sorbent. The sorbent material at x>0.45m still has unconverted CaO, but is not of use as the hydrogen concentration is below 90% (dry basis). In effect, though the maximum CO2 capacity of the material may be high, the useful CO_2 absorption capacity of the material is the kinetically fast portion that results in hydrogen concentration >90%.

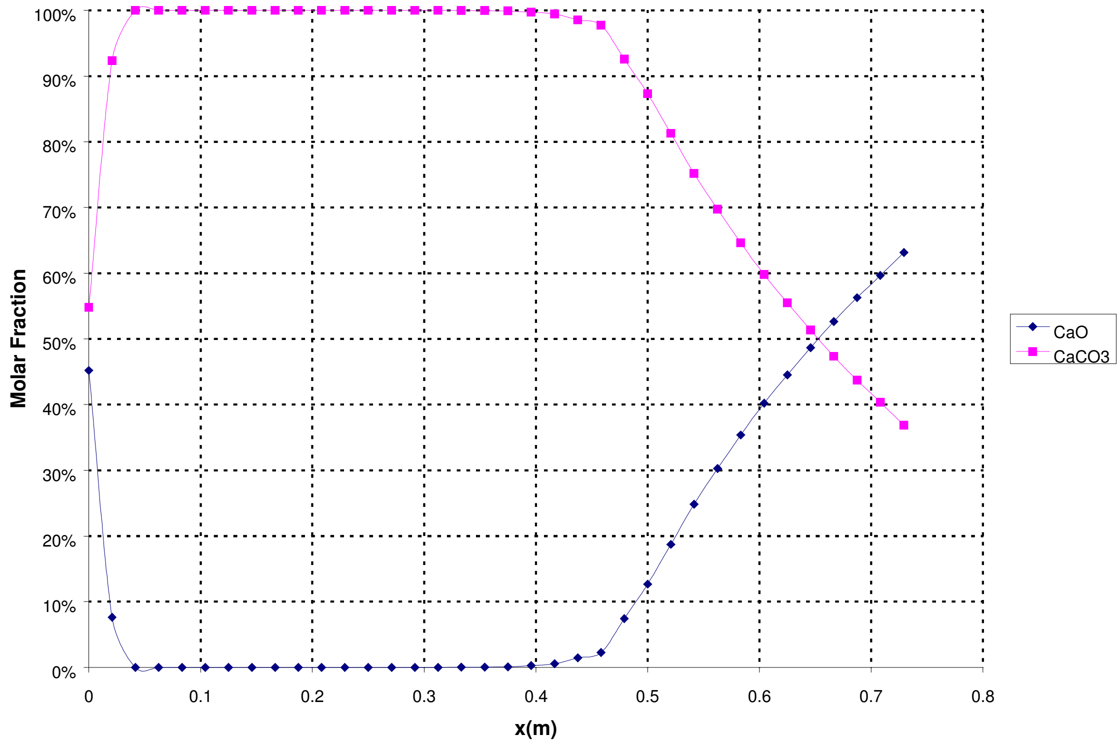


Figure 62: CaO and CaCO3 molar fraction profile at the end of reforming step

Figure 63 shows the CO_2 adsorption rate at selected reactor positions as a function of time. As can be seen from the figure, all sections of the bed show considerable activity in the early part of reforming step. We can also observe that a front with high rate of absorption progresses through the bed. At the end of reforming step, most parts of the beds have very low activity.

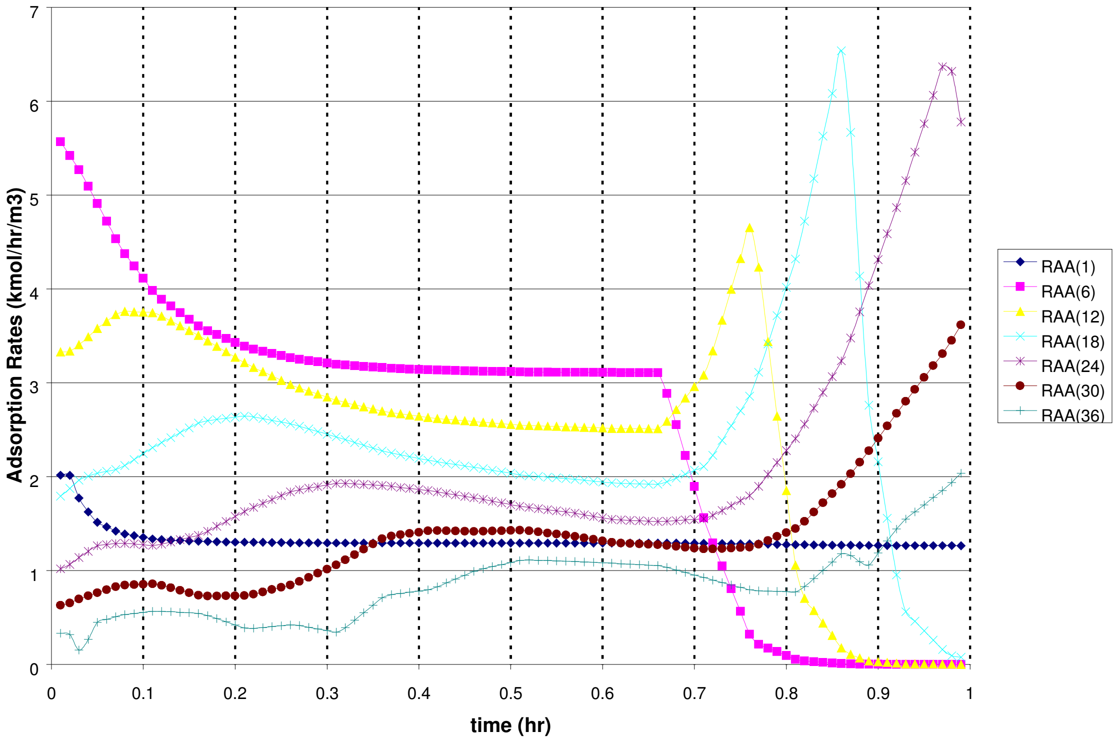


Figure 63: CO2 adsorption reaction rates with the time

Regeneration Results

When H_2 concentration decreases below 90%, the SSR bed is regenerated. Usually, the bed is regenerated at higher temperatures (>800^{o}C) to improve $CaCO_3$ calcination kinetics. Also, the regeneration step needs to be slightly shorter than the reforming time. Typical regeneration methods are steam regeneration, combustion gas regeneration, and *in-situ* combustion regeneration. The regeneration heat load includes the bed sensible heat and the CO_2 desorption heat. In this section, we have presented results from combustion gas regeneration.

Figure 64 shows the gas temperature profile as a function of time. At a bed temperature around 700^{o}C, the $CaCO_3$ calcination kinetics allow regeneration of most of the $CaCO_3$. The rate of heat supply determines the regeneration time. In early part of regeneration, the heat from the burner exhaust is used to heat the bed to regeneration temperatures. Once a section of the bed reaches regeneration temperature, most of the heat is used for CO_2 desorption. After section is regenerated, the heat is used to further raise the bed temperature and hence, shows rapid increase in temperature. After 1.94 h, all gas temperatures will be higher than 800^{o}C.

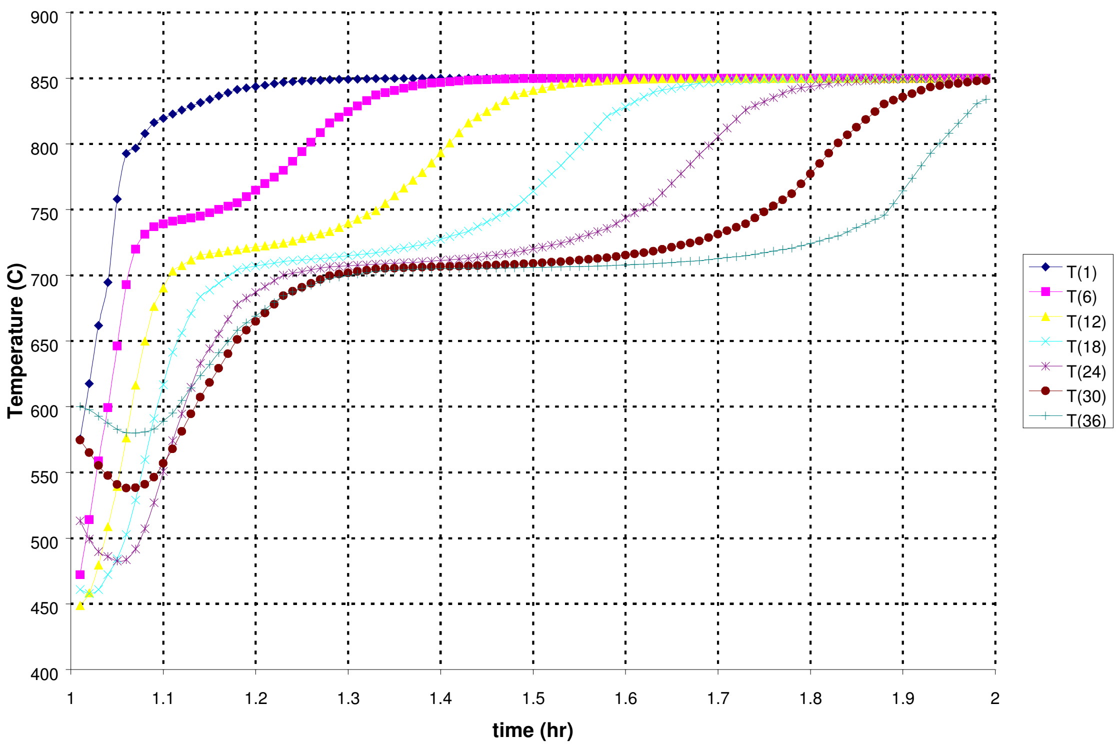


Figure 64: Gas temperature profiles during regeneration process

Similar to the absorption rate profile, the gas temperature profile also shows a temperature front progressing through the bed. This characteristic is also observed in desorption rate profile, shown in Figure 65. The positive reaction rate means that CO_2 is absorbed in the bed, while the negative reaction rates represents CO_2 desorption. It is clear that after the entrance part of the bed is fully regenerated, the front moves to the next segment, until this segment is also fully regenerated. Eventually, the regeneration front will move to the end of the reactor and is the end of regeneration step. It is worth noting that some CO_2 is adsorbed at the end of the reactor at the beginning regeneration step. This is due to CO_2 present in the combustion exhaust and lower temperatures at the end of the reactor being favorable for adsorption.

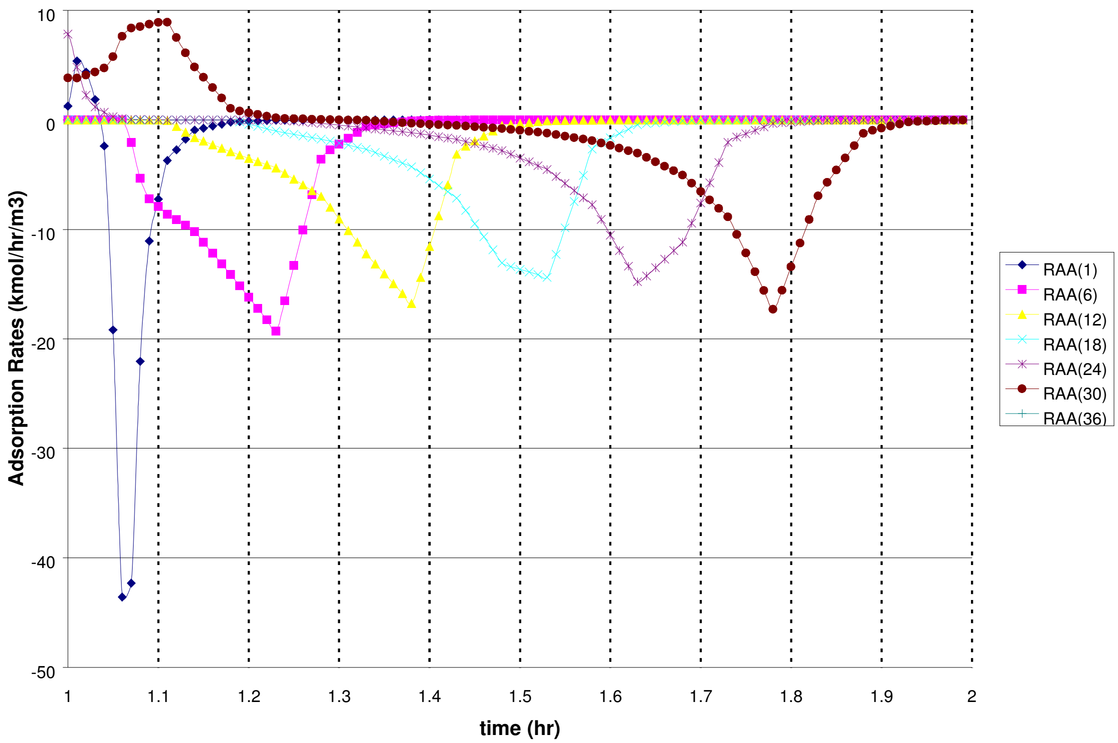


Figure 65: CO2 desorption rates with time

Figure 66 shows CO_2 concentration in the regeneration exhaust stream. Early in the regeneration step, CO_2 concentration increases reflecting the time required to heat the bed from reforming temperature (<600^{o}C) to regeneration temperature (700^{o}C). The flat portion of the curve is the stage where heat is consumed to regenerate the bed. After 1.8 h, the CO_2 molar fraction starts to drop and more heat is transferred from the gas phase to heat the bed to higher temperature. After 2 h, CO_2 concentration in the flue gas is equal to that of the input. At this point, the bed is considered fully regenerated.

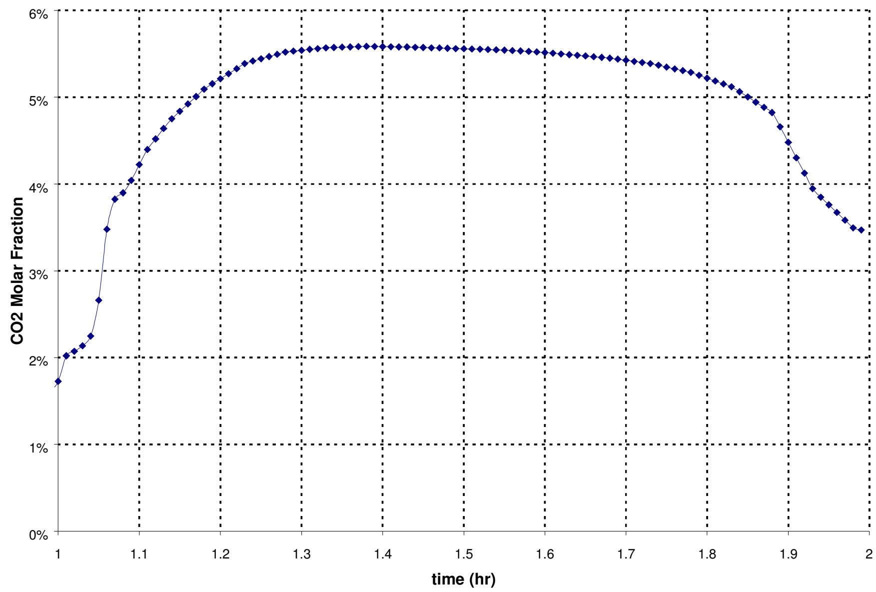


Figure 66: CO_2 concentration in flue gas during regeneration

SSR Regeneration Scheme Comparisons

As described earlier, numerous schemes can be used for regenerating the bed. In this section, we will compare three SSR regenerations schemes, i.e., the steam regeneration, the combustion gas regeneration, and the two-step regeneration. The two-step regeneration uses combustion gas regeneration followed by steam regeneration. The selection of the regeneration scheme will affect the system process integration, regeneration time and system efficiency. The dynamic model was used to compare the different regeneration schemes.

The assumptions for this analysis were:

(1) Starting bed temperature of 600°C
(2) S/C of 3 for reforming step
(3) 10 kg/day H_2 production capacity
(4) Reforming step is stopped and regeneration is triggered when H_2 dry concentration is <90%; average bed temperature is 523°C at this point
(5) Regeneration flow rate of 2.95 kmol/hr - combustion flue gas or pure steam depending on the scheme
(6) Inlet flue gas temperature during regeneration is 850°C
(7) Adiabatic reactor

Figure 67 shows the effluent temperatures as a function of time. Here, "steam" represents steam regeneration, "combustion" represents combustion flue gas regeneration, and "two-step" represents combustion flue gas regeneration followed by the steam regeneration. In all three cases, the regeneration flow rates were assumed to be 2.95kmol/hr. In two-step regeneration, combustion gas regeneration switches to steam regeneration once effluent temperature reaches 750°C. "Steam2" also stands for steam regeneration, but with lower flow rate (2.377kmol/hr). At this flow rate, steam has the same heat content (MC_P) as combustion gas (2.95kmol/hr).

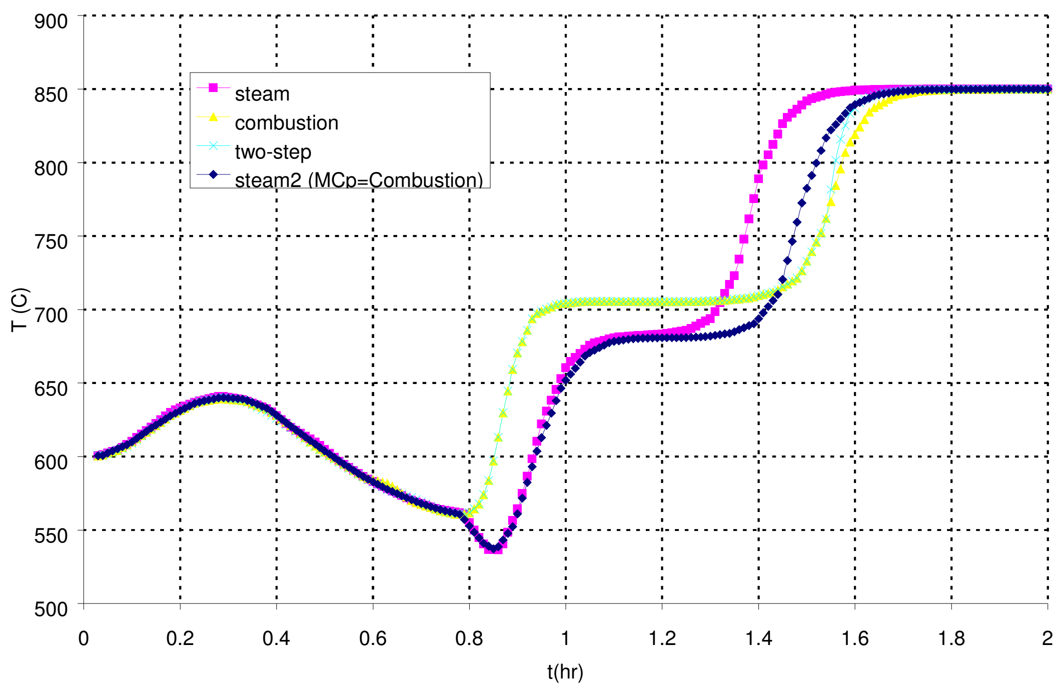


Figure 67: Effluent temperature with three regeneration schemes

As shown in Figure 67, the steam regeneration is the quickest of the three regeneration schemes. Two major reasons contribute to this result. First, in combustion gas regeneration some CO_2 from the exhaust stream will be absorbed by the sorbent material in early part of regeneration step. This problem does not exist in steam regeneration and hence, does not require the extra energy and time as in combustion gas regeneration. Second, for a given flow rate and ΔT across the bed, heat content (MC_P) of steam is higher than the combustion gas for the same molar flow rate, so steam can transfer more energy to regenerate the bed. For the same reason, steam2 regeneration method takes longer to complete the regeneration step. Our results show only a small advantage in using two-step regeneration over the combustion gas regeneration.

Figure 68 shows the total CO_2 adsorption/desorption with time. While adsorption and desorption may occur at different bed locations at same time, the positive values in the chart represent net CO_2 adsorption and the negative values represent net CO_2 desorption. It is evident that in combustion gas regeneration some net CO_2 is adsorbed in early part of regeneration. The quicker steam regeneration is due to larger heat content (MC_P). When same heat content (MC_P) is used in steam and combustion gas regeneration, the regeneration rates are very close. In all, it can be concluded that the total rate of heat supply is limits the regeneration time.

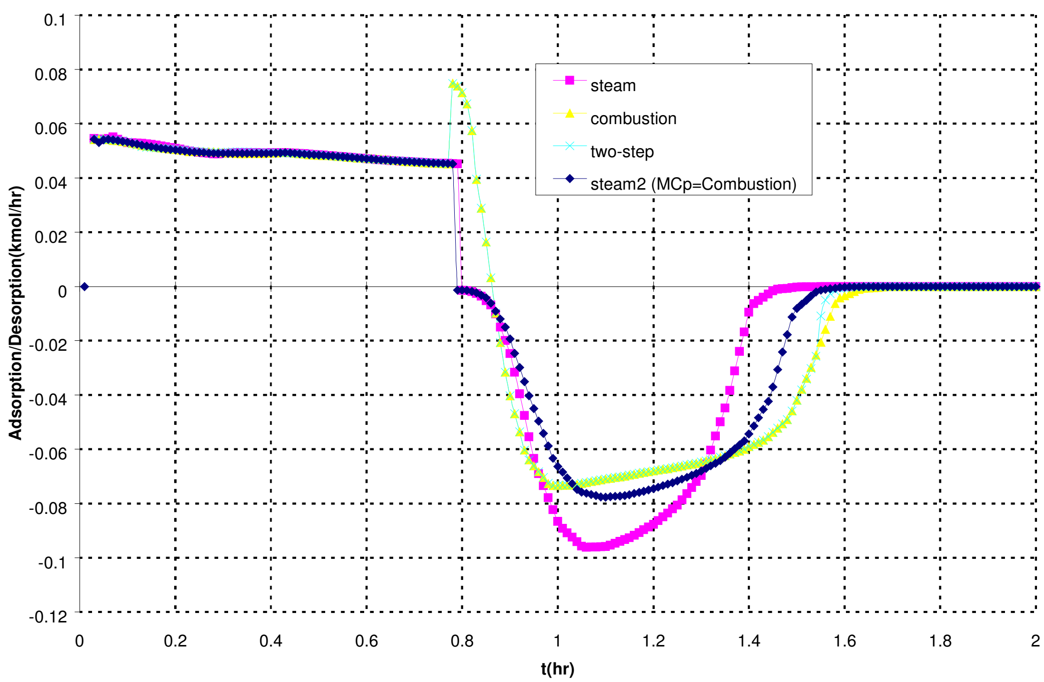


Figure 68: CO2 adsorption/desorption with three regeneration schemes

Figure 69 shows the effect of heat and mass transfer limitations on $CaCO_3$ regeneration time. On one extreme, we assumed that CO_2 mass transfer from the bed to the gas limits the regeneration, which could be due to low effective mass transfer coefficient or low $CaCO_3$ calcination kinetics. On the other extreme, we assumed that the heat transfer between the gas and the bed limits the regeneration. When the regeneration is mass transfer or kinetics limited, the bed is temperature rises more rapidly. On the other hand, when the regeneration is heat-transfer limited, the bed temperature rises slowly. Majority of the heat supplied by the regeneration stream is used for the $CaCO_3$ decomposition and the balance of the heat is used to increase the bed temperature. The curves between the mass transfer and the heat transfer limits have higher mass transfer coefficient than the mass transfer limit case.

Although the curves have different shapes, it is interesting to note that the effluent temperature will reach 800^{O}C about the same time in all the cases. Again, it shows that the total heat provided by the regeneration stream determines regeneration time.

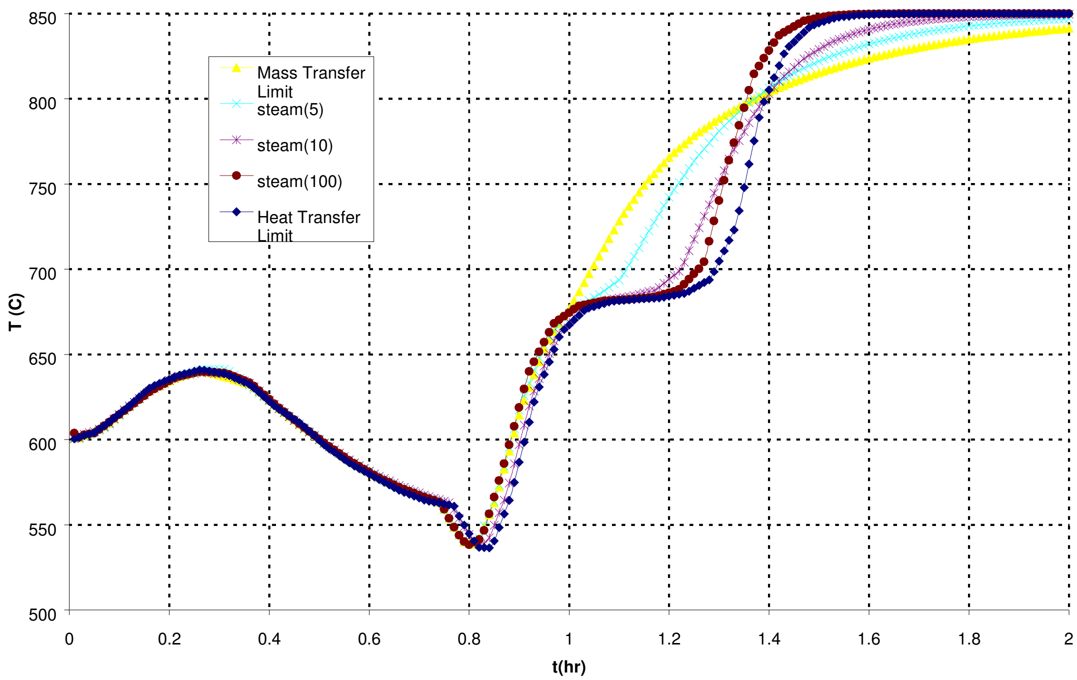


Figure 69: Effect of heat and mass transfer on CaCO3 decomposition

Steam Recycle Regeneration

Using high temperature steam to regenerate the $CaCO_3$ bed has the advantage of producing pure CO_2 and has the potential for CO_2 sequestration. But, the thermal efficiency is lower than the combustion gas regeneration because the latent heat of water cannot be fully recovered from steam. We studied steam recycle as a method to reduce the steam consumption.

In this method, a fraction of the steam regeneration effluent is recycled and mixed with fresh steam for the regeneration feed. Using the steam recycle can reduce the steam consumption, however, CO_2 will be present in the regeneration stream feed and this limits the extent of steam recycle.

Figure 70 shows the regeneration flue temperatures with different recycle ratios. The regeneration temperature plateau increases with the increasing steam recycle ratio. This is because the CO_2 partial pressure increases in the regeneration feed with higher recycle ratios. So higher bed temperatures are required to keep the CO_2 desorption equilibrium pressure higher than the regeneration feed CO_2 partial pressure. As seen from the figure, 50% recycle ratio almost takes the same time as 0% recycle to reach effluent temperature of 800°C, which is an indication that the bed has been fully regenerated. On the other hand, recycle ratio of 80% will take longer time to reach 800°C.

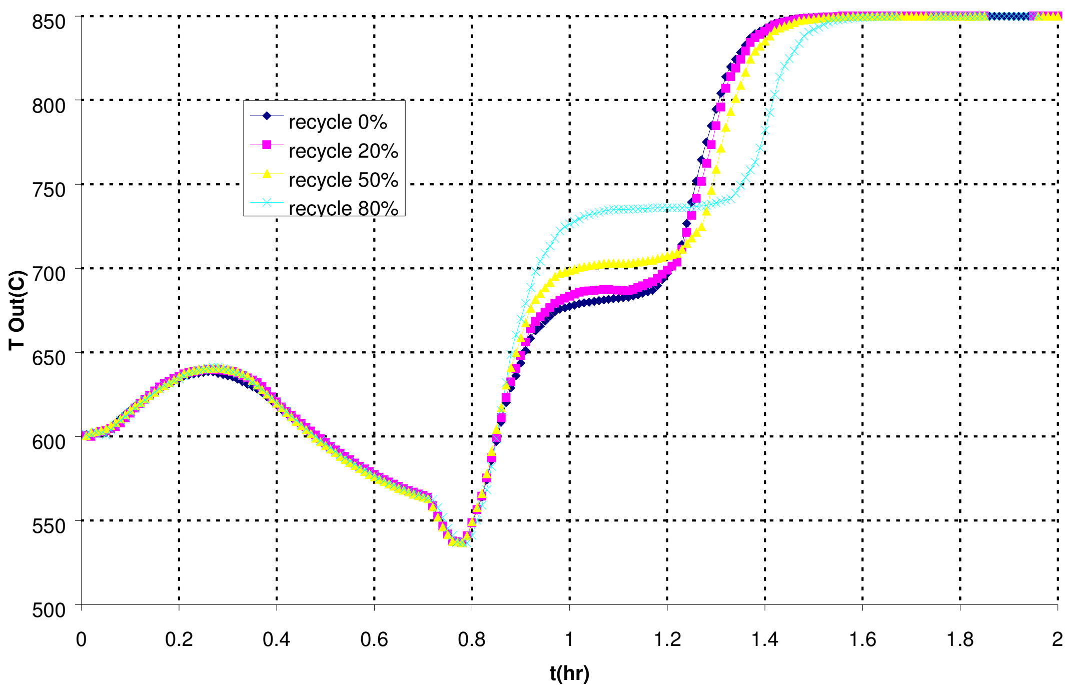


Figure 70: Regeneration effluent temperatures at different steam recycle ratios

Figure 71 shows the CO_2 adsorption and desorption rates with time for different steam recycle ratios. Again, it is easy to see that 50% steam recycle ratio can regenerate the bed in the same time as 0% recycle ratio, while 80% recycle takes a longer time.

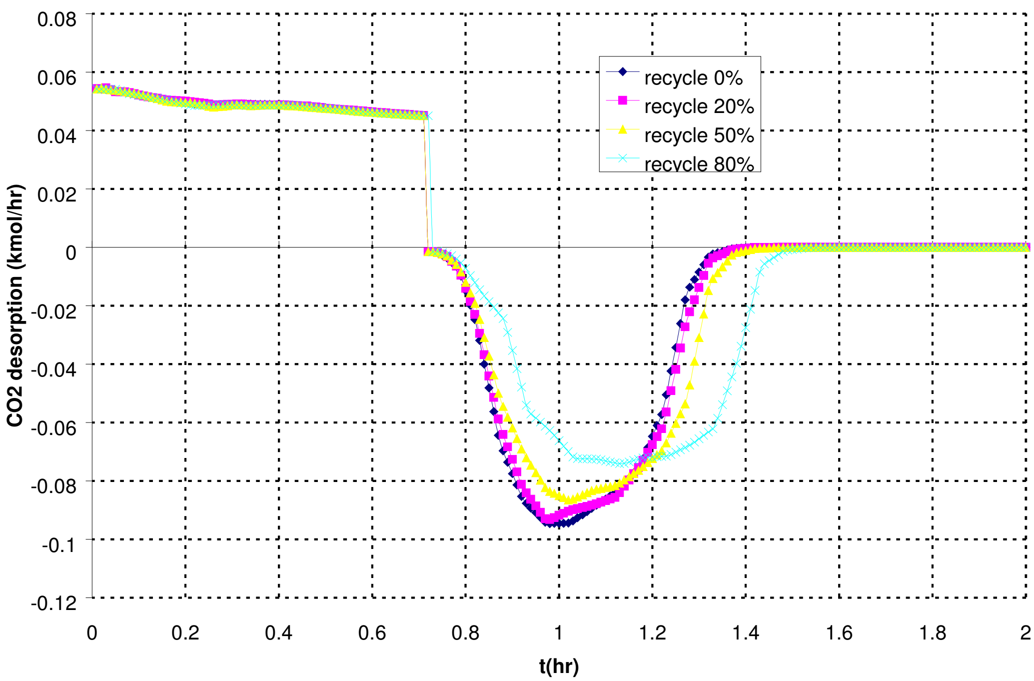


Figure 71: CO2 adsorption/desorption rates for different steam recycle ratios

Vacuum Steam Regeneration

When the regeneration gas has lower CO_2 partial pressure, the concentration gradient for the mass transfer is higher. Thus, the regeneration time can be decreased if the mass transfer is the dominating factor for the regeneration. One way to decrease the gas phase CO_2 partial pressure is to use the vacuum steam regeneration.

Figure 72 shows the SSR reactor effluent temperature changes as a function of regeneration total pressure. The reforming pressure is assumed to be the same in all the cases. Lower pressure leads to lower regeneration temperature plateau, resulting in more net heat transfer from the gas phase to the solid, for a given regeneration flow rate and temperature. As can be seen from Figure 72, the regeneration time (the time for the temperature to reach 800^{o}C) at 0.4 bar is 0.1 h faster than that at 1 bar.

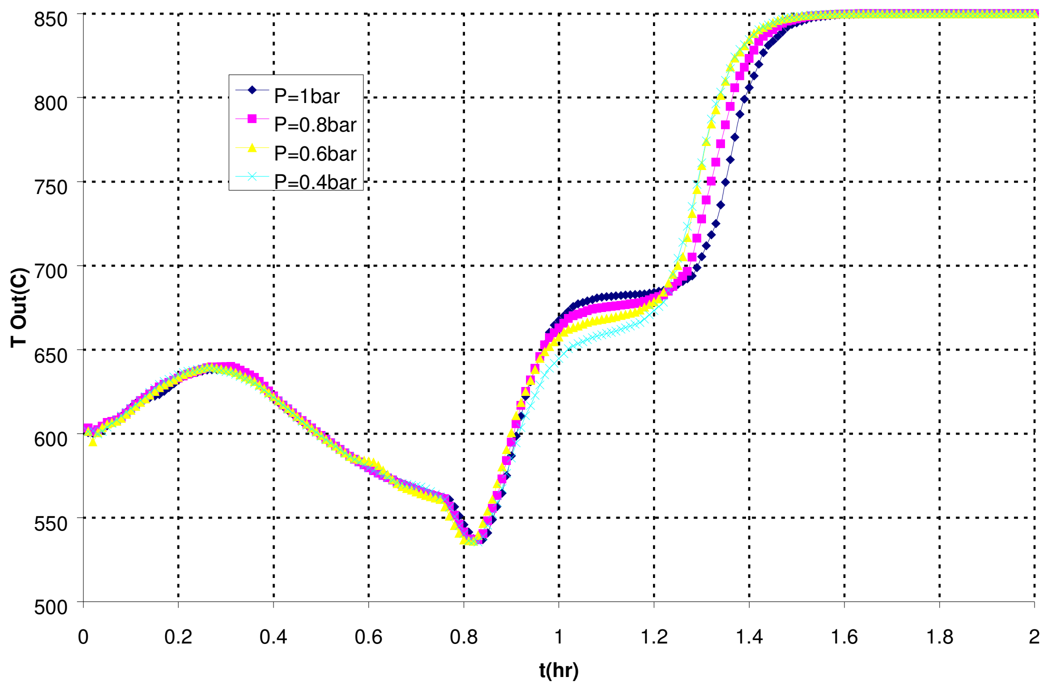


Figure 72: SSR reactor effluent temperatures with regeneration under vacuum pressures

Figure 73 shows the CO_2 adsorption and desorption rates under different regeneration vacuum pressures. The maximum regeneration rate (CO_2 desorption rates) at 0.4 bar is higher than that at other pressures. However, regeneration time at 0.4 bar is only slightly smaller than that at other pressures, showing that the total heat transfer capacity of the regeneration gas determines the regeneration time.

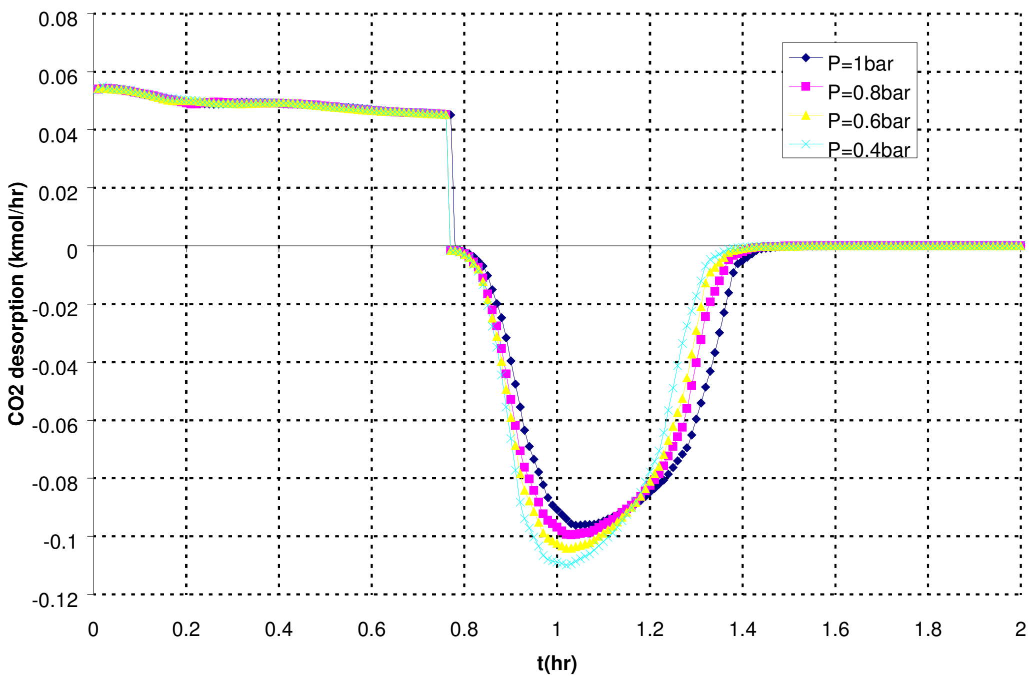


Figure 73: CO2 adsorption and desorption rates with different regeneration vacuum pressures

SSR Reactor Cooling - Base Case Simulation results

The SSR bed will be at high temperature (>800°C) after full regeneration. At this high temperature, CO2 absorption is not favored and hence, not an optimum condition for SSR. So an intermediate cooling step is necessary to bring the temperature down to optimum reforming conditions.

Air was assumed to be the cooling stream. As CO2 concentration in air in very low, CO_2 adsorption during cooling is insignificant. Thus, the process is gas-solid heat transfer without any chemical reactions. Figure 74 shows the gas temperature profile as a function of time during the cooling process. As seen from the figure, the entrance part of the bed cools down to inlet air temperature in 0.1 h, while the end of the bed takes about 0.5 h. In a system, we do not have to cool the bed to room temperature, and the result presented in the figure is just an illustration of the bed and gas temperature behaviors during the cooling process.

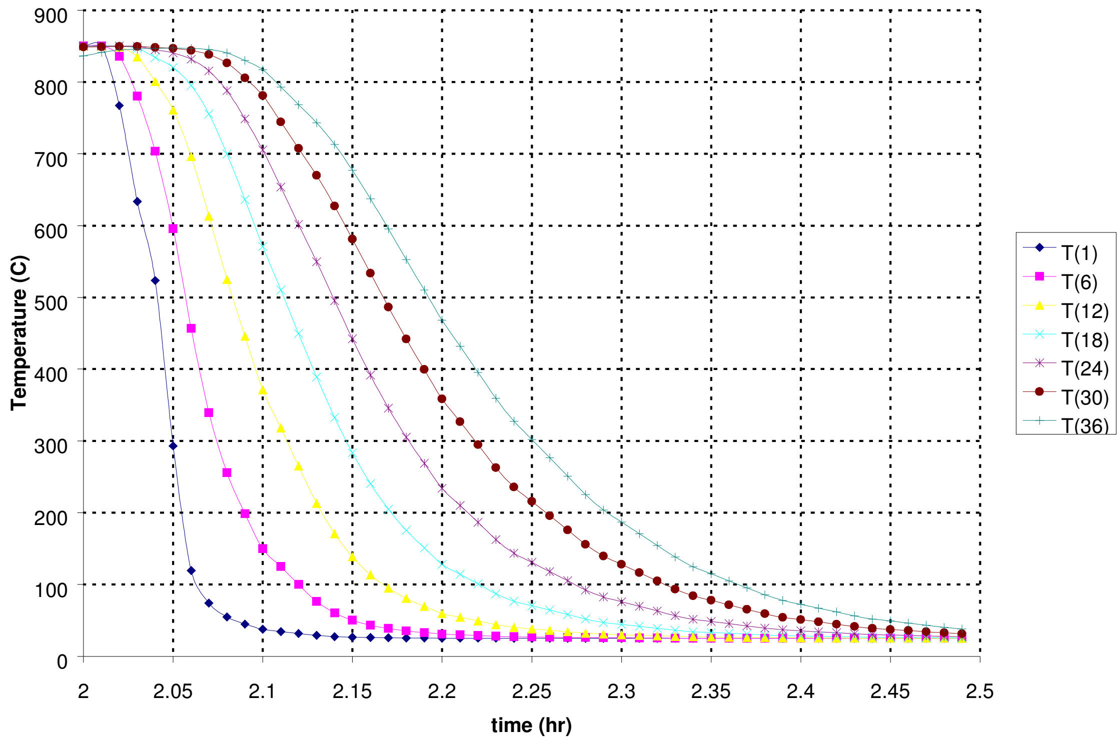


Figure 74: Gas temperature profile during cooling step

Co-flow cooling & reforming step

Figure 75 shows a typical SSR cycle, which consists of a regeneration step, cooling step and a reforming step. All inlet flows are in the same direction.

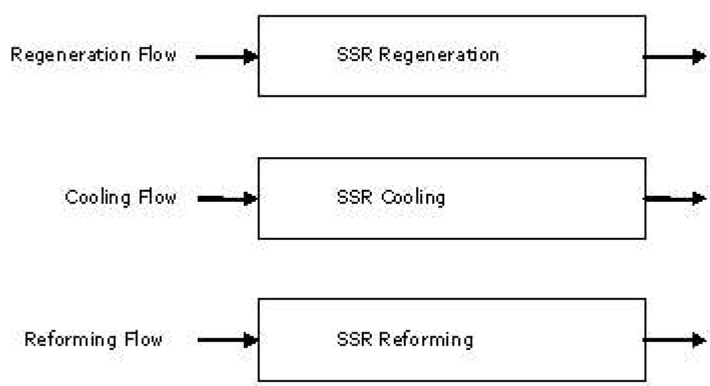


Figure 75: A typical SSR cycle

As mentioned before, the bed temperatures at the end of regeneration step are about 850°C. We assumed a stream with inlet temperature of 600°C to cool the bed. Figure 76 shows the temperature profile after the cooling step. At the end of cooling step, inlet part of bed is cooled down to the inlet stream temperature, while the end of bed is still at 740°C. The cooling step could continue till all of the bed is close to 600°C, but it will increase the cycle time and is not the optimum in terms of recovering some of the bed heat in the reforming step.

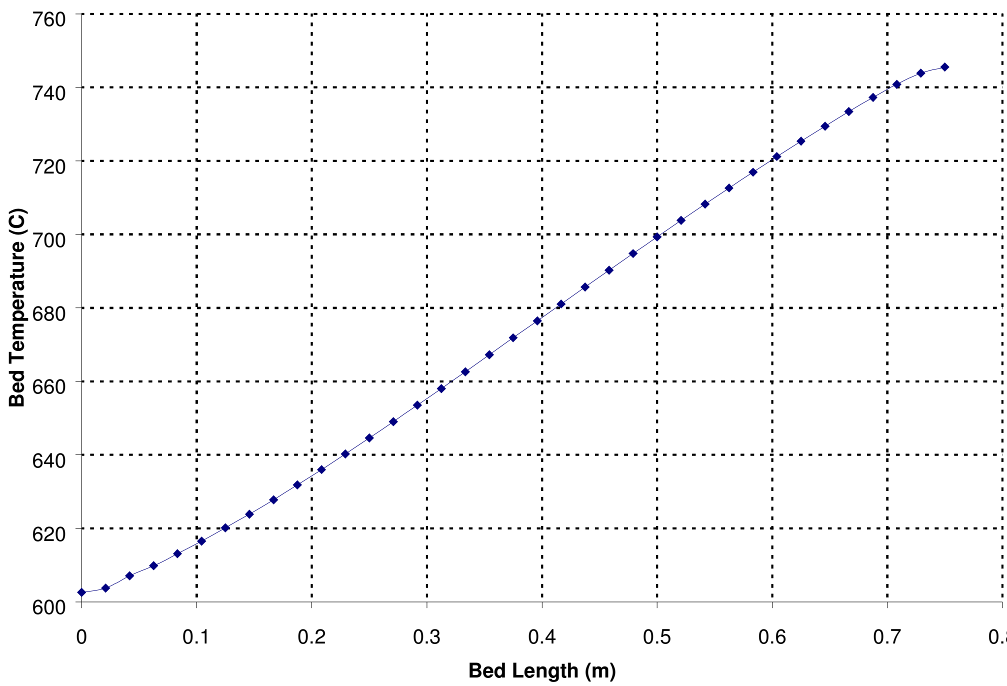


Figure 76: Temperature profile after co-flow cooling step

The reforming step follows the cooling step. We studied two cases for the reforming step: first, reforming flow in the same direction as regeneration and cooling flows (referred to as co-flow); second, reforming flow is opposite in direction to regeneration cooling flows (referred to as reverse flow).

Figure 77 shows the reactor effluent temperature as function of time, for co-flow and reverse flow reforming cases. In the figure, we focus on the second reforming cycle, t > 1.8 h. The effluent temperature in co-flow decreases continuously from 700°C to 570°C. In reverse flow effluent temperature initially increases and then decreases, similar to the co-flow case.

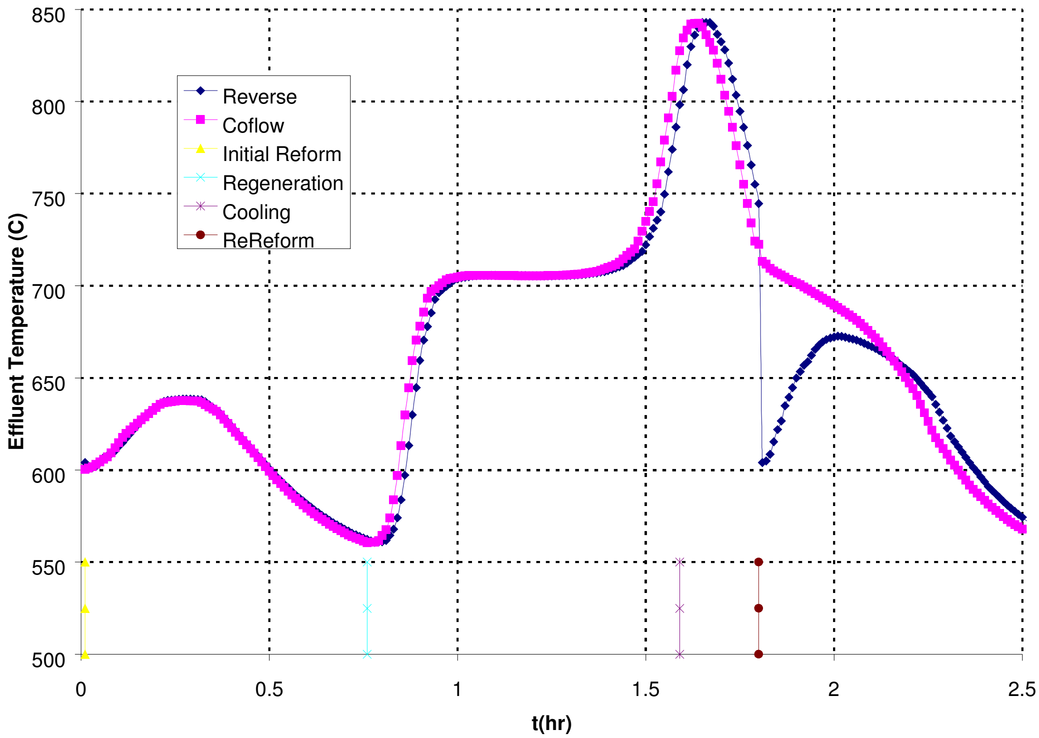


Figure 77: Reactor effluent temperature co-flow and reverse flow reforming

Figure 78 shows the H_2 concentration with time, corresponding to Figure 77, for co-flow and reverse flow reforming cases. Although reverse flow has higher initial H_2 concentration, the average of H_2 concentration is almost same in both cases.

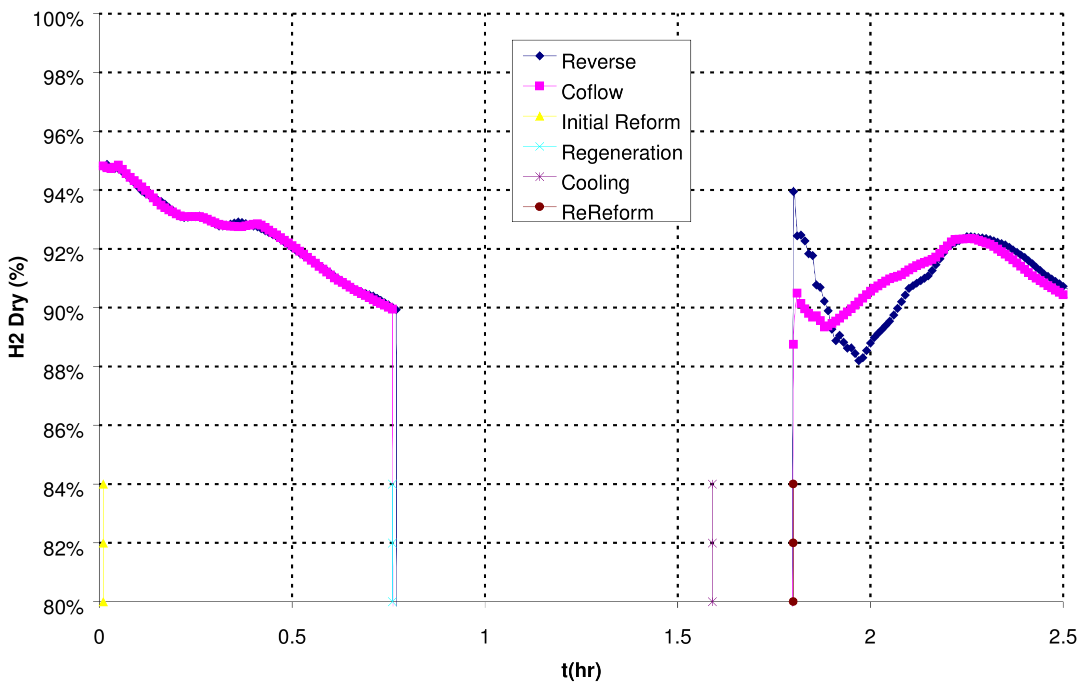


Figure 78: H_2 concentration for co-flow and reverse flow reforming cases

Reverse flow cooling & reforming step

Another way to implement the inter-step cooling is to use reverse flow for the cooling stream, as compared to regeneration flow direction. The flow configuration is shown in Figure 79. The reforming and the regeneration flow is assumed to be in the same direction but cooling flow is assumed to be in the opposite direction.

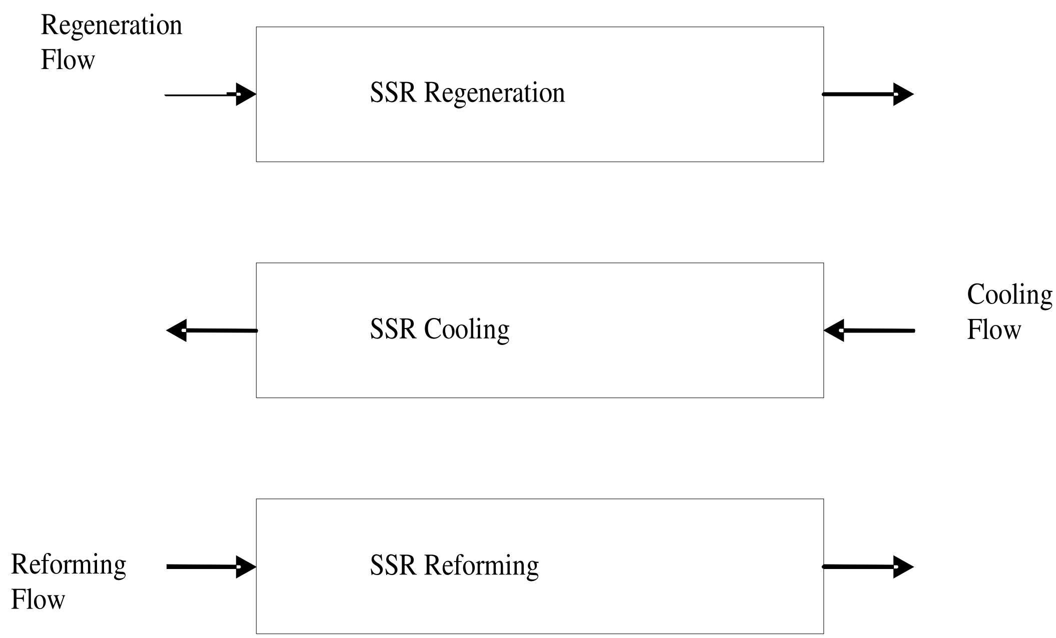


Figure 79: Reverse cooling flow configuration

Optimum temperature profile with reverse flow cooling is established in a shorter time and hence, shortens the cooling step. After a quick cooling process, the left side (refer to Figure 74) of the bed is close to the regeneration temperature (850^{o}C), while the right side of the bed will be close to the cooling flow inlet temperature.

Figure 80 shows the bed temperature profile after reverse cooling process (0.1 h), for different inlet flow temperatures. When the reforming process starts subsequent to cooling, the high bed temperature on the left side of the bed provides extra favors steam reforming; and the relatively low temperature on the right side of the bed is more favorable for the CO_2 adsorption. This helps with high methane conversion and high CO_2 adsorption efficiency, and results in higher and more uniform hydrogen purity over the reforming cycle.

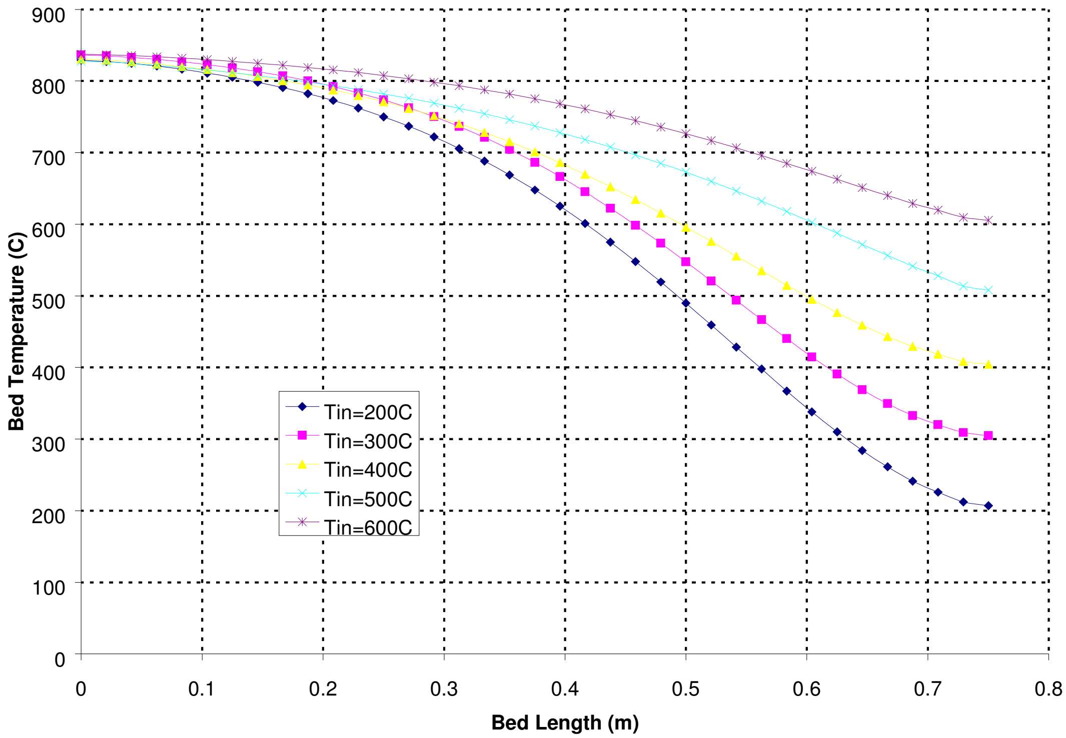


Figure 80: Bed temperature profile after reverse flow cooling

Figure 81 shows the simulation results of hydrogen purity after the methanator with different bed temperature gradients (refer to Figure 80). It is evident that the hydrogen purity is highest when low temperature (200^{o}C) reverse flow cooling is used.

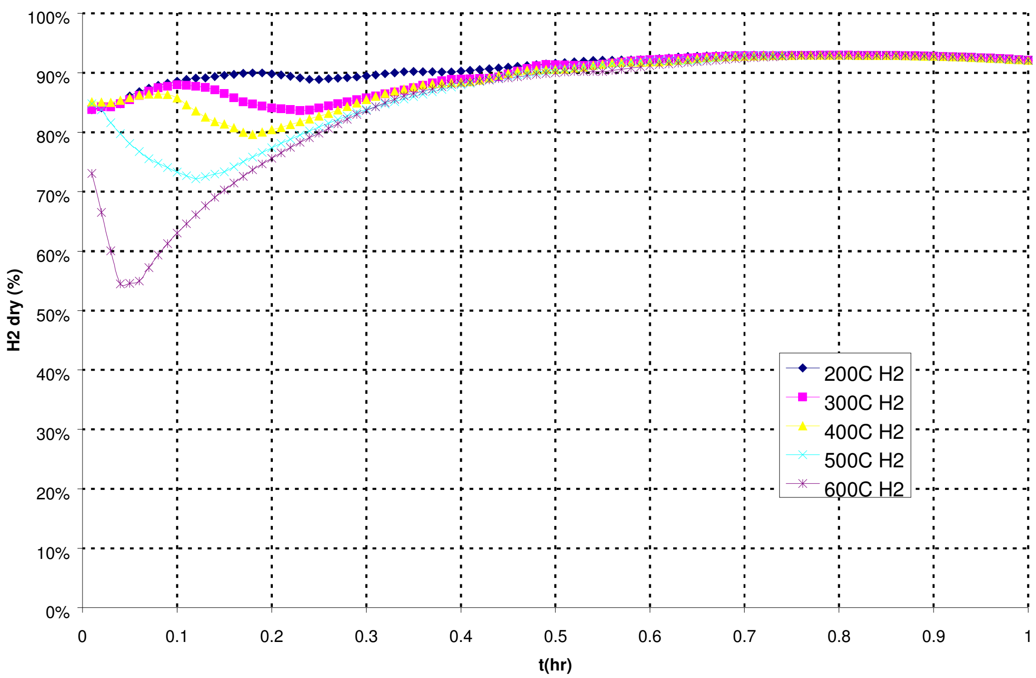


Figure 81: H_2 concentration with different reverse flow cooling inlet temperatures

Effect of Prereformer on Single Step Reforming

Figure 59 shows a typical H_2 concentration profile as function of time. As can be seen from the figure, the H_2 concentration reduces significantly after 0.4 h. At the same time, CO and CO_2 concentration increase only slightly, compared to relatively large increase in CH_4 concentration. This is due to decrease in methane conversion resulting from low bed temperature.

Two major reactions in a SSR reforming reactor are SMR and CO_2 adsorption. The SMR reaction is endothermic (ΔH=206kJ/mol) and CO_2 adsorption is exothermic (ΔH=-178.3kJ/mol). Thus, the overall reaction is slightly endothermic. From Figure 50, we can see that the optimum temperature for reforming in SSR is between 550°C to 600°C. Too high a temperature leads to less effective CO_2 adsorption, while too low a temperature leads to low CH_4 conversion. Besides the SMR reaction and CO_2 adsorption, two factors that contribute to the total heat balance are the bed temperature at the start of reforming and the reforming feed temperature.

Therefore, SSR heat balance equation includes sensible heat of the bed, heat content of reforming feed stream, heat of reaction for SMR and heat of reaction for CO_2 adsorption and heat content in the reformate stream. If we assume a reforming feed temperature and uniform bed temperature of 600°C, heat balance will not be satisfied and leads to a lower overall temperature. This causes a quick decrease in H_2 concentration after t>0.5 h.

Different options for improving the heat balance in the system are: (1) a heated prereformer; (2) higher inlet temperatures without prereformer; and (3) higher inlet temperatures with prereformer. Figure 82 represents all the options in a single scheme.

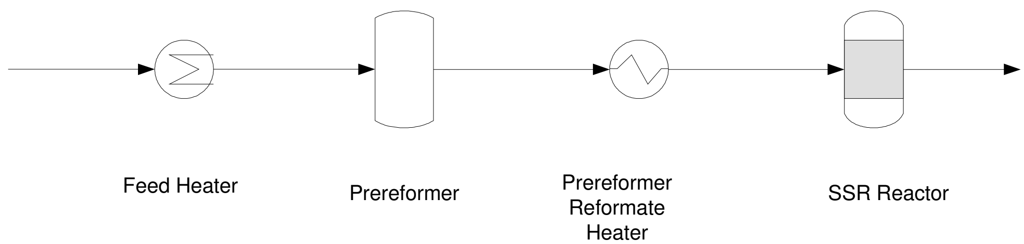


Figure 82: Scheme to improve heat balance in SSR

Heated Pre-reformer

Figure 83 shows the effects of CH_4 conversion in the prereformer on H2 purity in the SSR reformate. It is shown that H_2 purity at CH_4 conversion of 10% in the performer is higher than other cases presented, indicating the optimum CH_4 conversion in the prereformer.

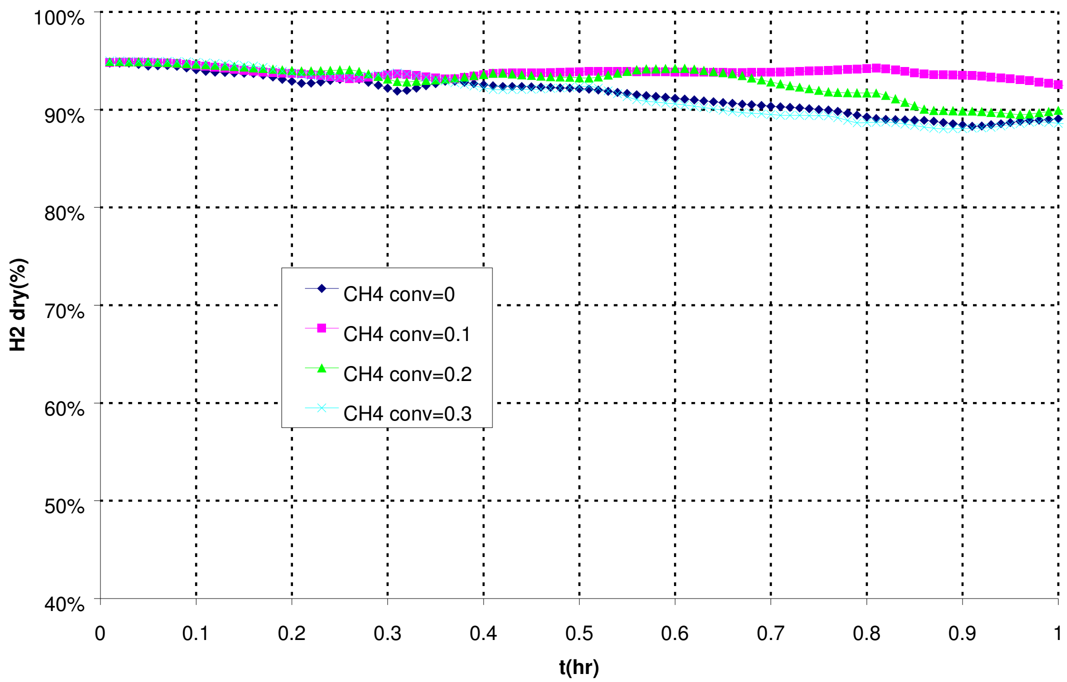


Figure 83: H2 purity as a function of CH4 conversions in the prereformer

Effect of Higher Feed Temperature

Figure 84 shows end of period and average H_2 concentrations (dry basis), after 1h reforming (end of reforming step), as a function of inlet temperatures. This simulation assumed the bed starting temperatures of 625°C and S/C of 3.5. Compared to the base case results with feed temperature of 600°C, higher feed temperatures result in higher H_2 concentration. Maximum average H_2 concentration occurs at feed temperatures between 680°C to 700°C and hence, the optimum inlet temperature for the reforming step.

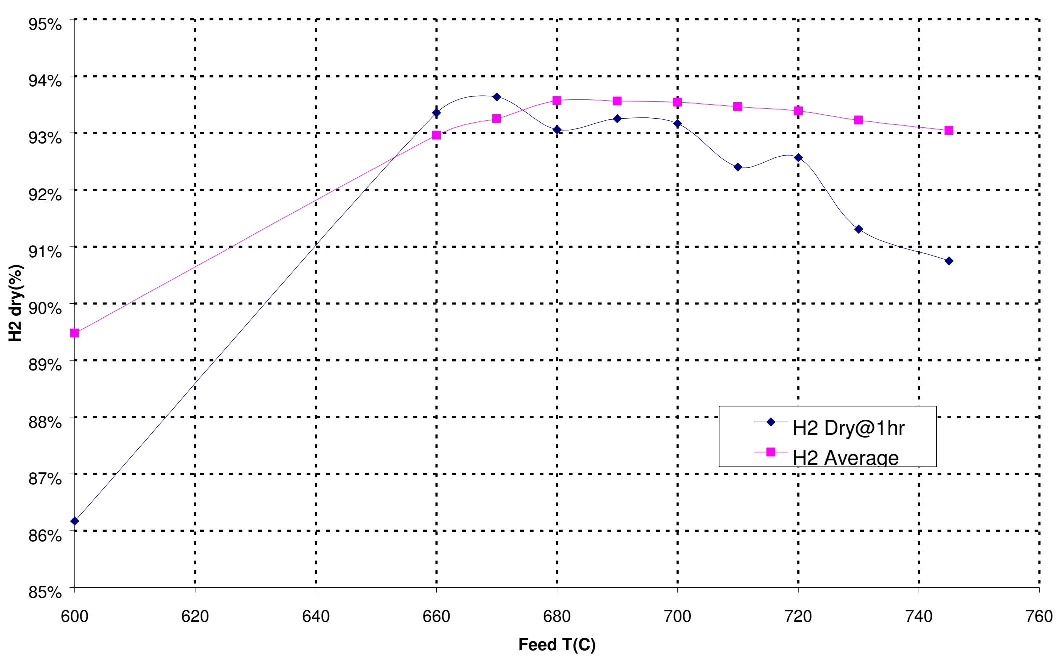


Figure 84: H2 concentration as a function of feed temperatures; initial Tbed=625°C and S/C=3.5

Effect of Higher Feed Temperature and Pre-reformer

Figure 85 shows the H_2 concentration (dry basis) as a function of initial bed temperatures at reforming inlet temperature of 690°C, pre-reformer heat power of 0.35kW and S/C of 3.5. It shows that the average H_2 concentration is maximum when initial bed temperatures is 575°C. The initial low bed temperatures are favorable for the CO_2 adsorption. Higher feed temperature and heating power helps with methane conversion. Combinations of these two factors lead to higher average H_2 molar fraction.

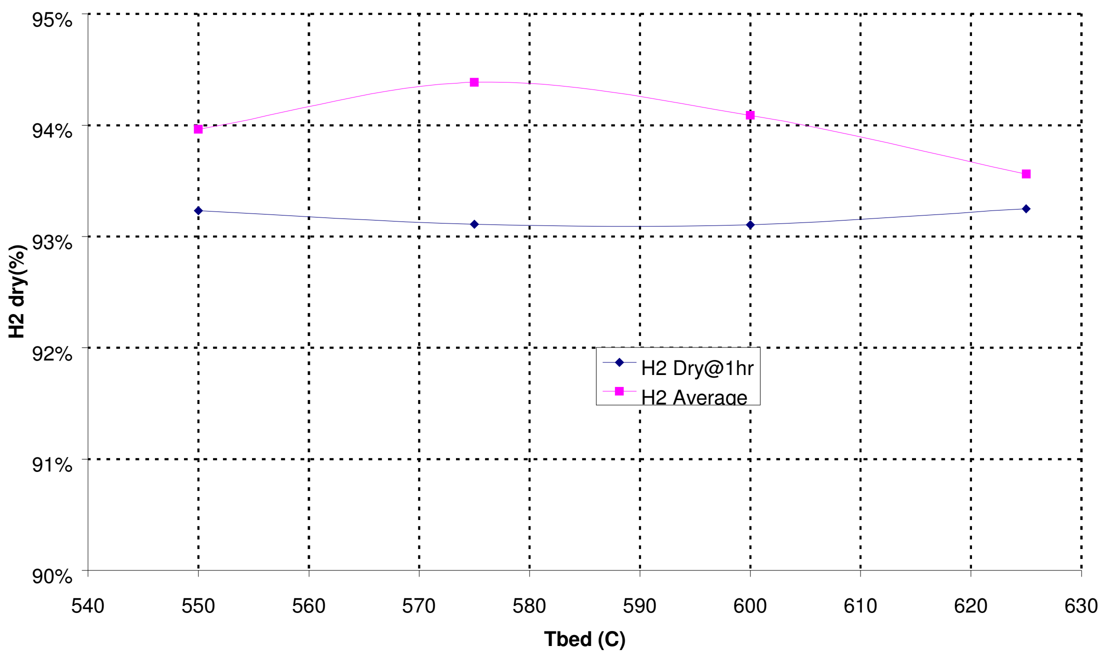


Figure 85: H2 concentration (dry basis) as a function of initial bed temperature; Inlet T=690°C, pre-reformer heat power Q=0.35kW and S/C=3.5

From analyses presented above, it can be concluded that:

(1) The optimum feed temperatures to obtain sustainable high H_2 concentration depends on the SSR reforming heat balance.
(2) The heat balance factors include the reforming feed temperature, the initial bed temperature, the SMR conversion, the water-gas-shift conversion and the CO_2 fixing efficiency.
(3) Different optimum feed temperatures exist for different initial bed temperatures.

Subtask 4.2: Efficiency Analysis

Process and System Modeling

The goal of process and system modeling work is to find the highest possible efficiency by optimizing the thermal integration scheme and operating conditions. A typical SSR cycle includes a reforming process, a regeneration process and inter-step cooling process.

For the reforming process, the operating parameters that can affect the system efficiency include operating pressure, operating temperature, steam-to-carbon ratio (S/C), and CO_2 adsorbents properties, including density, specific heat, CO_2 adsorption capacity, porosity and specific area (the surface area to the volume ratio). These parameters also affect the hydrogen purity, CH_4 conversion, and CO and CO_2 concentration. In the process and system modeling, we used the non-equilibrium model introduced earlier to simulate the reforming reaction.

For the regeneration process and for the overall process, the regeneration method is the dominant factor in determining overall system efficiency. The regeneration methods that we explored include steam regeneration, combustion gas regeneration and in-situ combustion regeneration. For the cooling process, the goal is to have the adsorbent bed at optimum temperature for CO_2 absorption and SMR at same time.

To accomplish the above process and system modeling task, we used Aspen Custom Modeler® (ACM). ACM is necessary here because it can conveniently incorporate the non-equilibrium reforming reactor.

Process and System Design

The packed bed in the SSR reactor has CO_2 adsorbents and reforming catalyst. The CaO adsorbents in the packed bed adsorb CO_2. After the bed is full, the adsorbent is regenerated prior to next reforming cycle. Between the regeneration and reforming steps, the bed is cooled from regeneration temperature to reforming temperature. Thus, the packed bed SSR is a cyclic process which involves the reforming, the regeneration and the cooling.

Figure 86 shows the flow diagram for a one reactor/modular system. This system will cycle between reforming and regeneration modes. The advantage of this system is that it requires fewer high temperature valves and system components. The disadvantage is that the thermal efficiency is not as high as in a two-reactor system. If only one modular reactor is used, hydrogen storage is required for continuous H_2 supply. This system is used as a base case for comparing the relative advantages/disadvantages of different regeneration schemes.

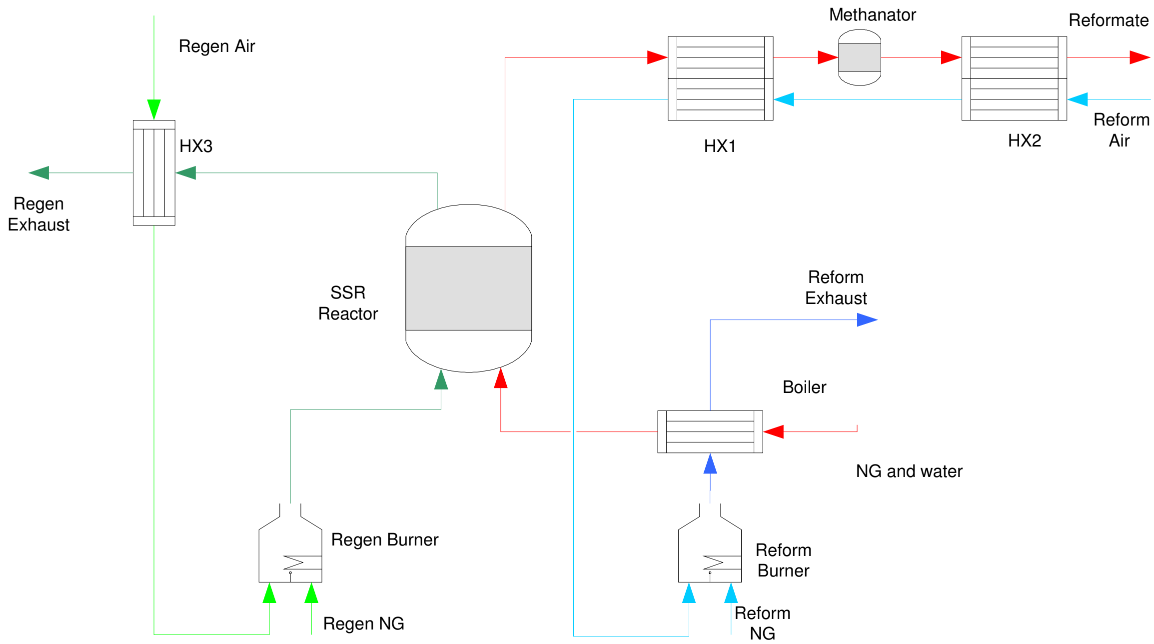


Figure 86: Modular/single reactor system for combustion gas regeneration

Regeneration Methods Comparisons

Combustion gas regeneration is shown in Figure 86. Figure 87 shows the steam regeneration method. The advantage of steam regeneration is the pure CO_2 generation and its potential to sequester CO_2 for large H_2 plants.

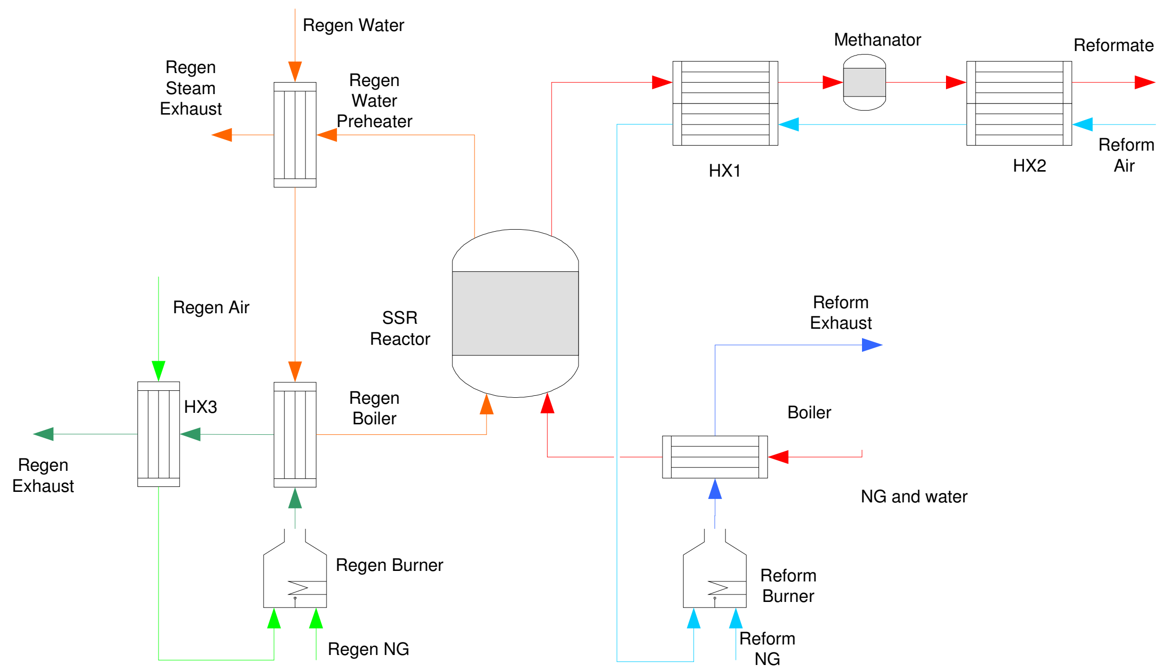


Figure 87: Modular/single reactor system for steam regeneration

We also studied the hybrid (combustion gas followed by steam) approach to regenerate the bed. The flow diagram for the hybrid regeneration is similar to Figure 87. The only difference, in hybrid regeneration, is that reforming burner and steam boiler are used in the regeneration mode.

The results from system analysis are shown in Table 6. The reforming operating conditions were assumed to be the same. Methanator was not included in this model. Thermal efficiency is defined as H_2 heating value divided by the total CH_4 heating value (including CH_4 feed to the process, reforming burner and regeneration burner). Thermal efficiency calculation takes credit for any unconverted CH_4 and CO heating value in the reformate.

Parameters	Units	Steam Regeneration	Hybrid Regeneration	**Combustion Regeneration**
Reform feed H_2O flow	kmol/hr	2.016	2.016	**2.016**
Reform feed NG flow	kmol/hr	0.672	0.672	**0.672**
Reform NG Fuel flow	kmol/hr	0.126	0.126	**0.126**
Reform Air flow	kmol/hr	5.7	5.7	**5.7**
Reform Air Compressor P	bar	1.2	1.2	**1.2**
Regen NG flow	kmol/hr	0.848	0.300	**0.210**
Regen Air flow	kmol/hr	25	25.2	**28**
Regen Air Compressor P	bar	1.4	1.4	**1.4**
Regen H_2O flow	kmol/hr	28	2.016	**0**
H_2 flow in reformate	kmol/hr	2.444	2.444	**2.444**
CH_4 flow in reformate	kmol/hr	0.058	0.058	**0.058**
CO flow in reformate	kmol/hr	0.013	0.013	**0.013**
Reform Air Compressor	kW	2.593	2.593	**2.593**
Regen Air Compressor W	kW	8.443	8.510	**9.456**
Thermal efficiency (LHV)		46.5%	71.1%	**77.9%**

Table 6: Comparison of different regeneration methods

Table 6 shows that the thermal efficiency is much lower with steam regeneration as compared to combustion regeneration. The efficiency of the hybrid regeneration scheme lies between them. The efficiency in steam regeneration is lower due to the significant amount of heat involved in generating steam and the inability to recover this heat completely from the exhaust. Figure 88 also shows the thermal efficiency of the system with different regeneration conditions.

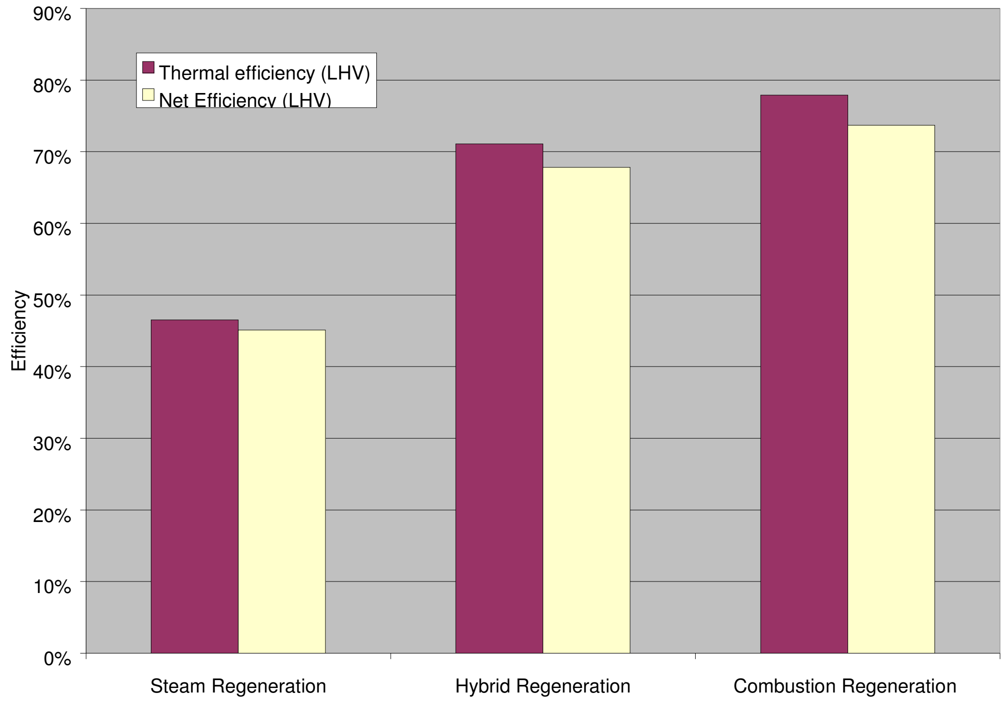


Figure 88: Thermal efficiency with different regeneration methods

Clearly, combustion gas regeneration has the potential for highest efficiency.
Therefore, we decided to pursue combustion gas regeneration system for our detailed engineering study.

SSR and Pressure Swing Adsorption (PSA) System Integration

We modeled SSR system integration with a PSA to predict efficiency of pure H_2 production. Two system integration scenarios were studied; high pressure reforming with PSA and low pressure reforming with PSA. We modeled this system with controlled oxidation for regeneration step. Figure 89 shows a typical flow diagram for integrating SSR and PSA.

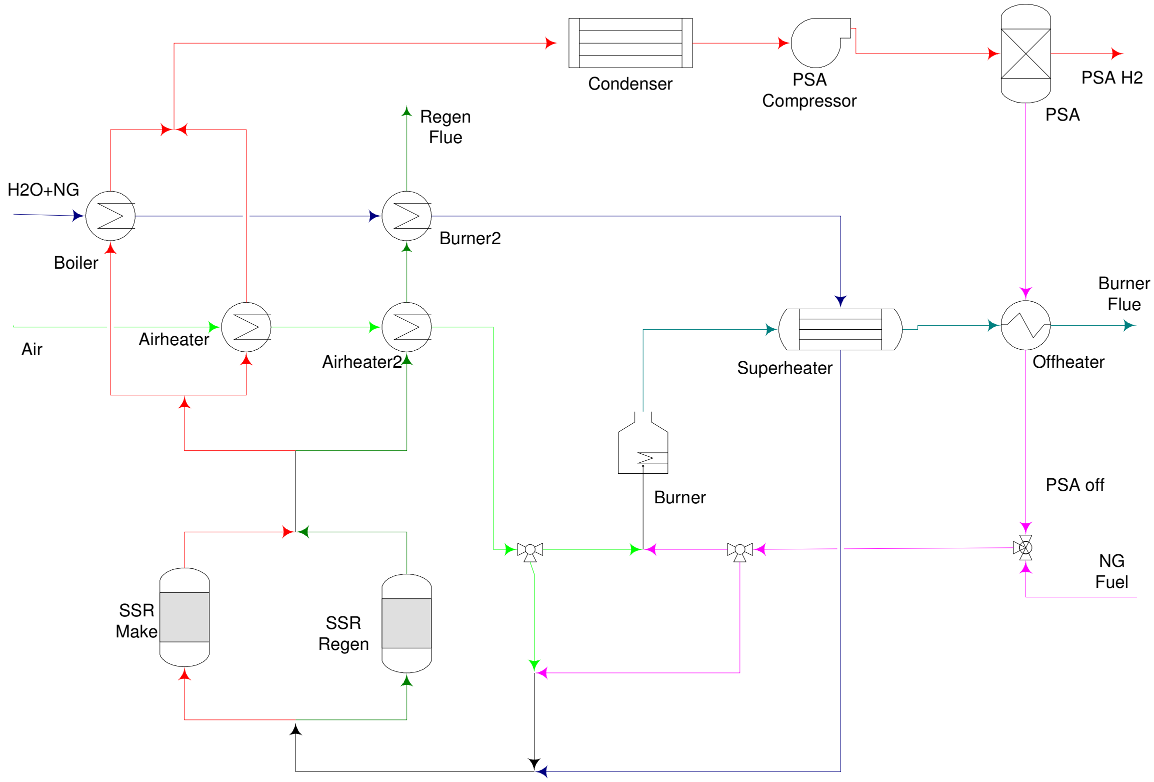


Figure 89: Flow diagram for SSR integration with PSA

Following assumptions/basis was used in this systems analysis:

(1) SSR reactor is an equilibrium reactor with the outlet temperature at 600°C

(2) SSR reactor, controlled oxidation and burner are adiabatic reactors

(3) SSR feed temperature is determined by heat balance of the reforming endothermic heat and CO_2 adsorption heat to maintain the reformer exit temperature at 600°C

(4) Heat duty of the controlled oxidation is determined by total CO_2 desorption heat (equal to CO2 adsorption heat in the reforming) and sensible heat required to heat the SSR bed from 600°C to 800°C

(5) All heat exchangers are physically possible

(6) Heat losses to the environment are negligible

(7) Rigorous model for PSA, which considers the effects of pressure, feed gas compositions and two layers of adsorbents (active carbon and zeolite)

(8) No pressure drop is considered at this stage of analysis

High Pressure Reforming with PSA

In this case, the reforming reaction is carried out at a high pressure to match PSA operating pressure. The methane conversion is lower at higher pressures. So, S/C of 4 is used in the high pressure scenario to improve the methane conversion. The reforming and PSA operating pressures were assumed to be 7.7 bar. PSA hydrogen recovery was about 80%. The summary of the thermal efficiency analysis is shown in Table 7.

NG Feed	0.8	kmol/hr
NG Fuel	0	kmol/hr
NG Total	0.8	kmol/hr
Total Power Consumption	3.041	kW
NG Feed compressor	1.952	kW
H_2O Pump	0.015	kW
Air Compressor	1.074	kW
NG Fuel Compressor	0.000	kW
PSA compressor	0.000	kW
H_2 Production	2.196	kmol/hr
Thermal Efficiency (LHV)	81.4%	

Table 7: Thermal efficiency analysis of high pressure reforming + PSA

Table 8 shows the energy balance for high pressure reforming with a PSA system. The total energy input include the natural gas (methane) lower heating value (LHV), a small amount of the sensible heat in natural gas and air and power inputs for compressors and pumps. As can be seen from the table, most of the inlet energy is converted to H_2 resulting in a system efficiency of about 81.4%.

The sensible heat content in burner effluent, regeneration effluent and PSA H_2 add up to 4.0% of total energy output. The bed loss term stands for the heat required to raise the SSR bed from reforming temperature (600^{o}C) to calcination temperature (800^{o}C). It is a loss term as we assumed that we cannot recover this heat and bed loss is 1.4% of the total energy output. The heat loss in the condenser, which is used to separate liquid water from vapor before the PSA or the PSA compressor, is 2.3% of the total energy output. For high pressure reforming, reformate compressor is not needed. "Others LHV" term stands for LHVs from other trace combustible gases such as CH_4 and CO contained in the PSA H_2 stream, burner and regeneration effluents and condensates from the condenser. The "water latent heat" term represents the latent heat of condensation contained in the burner and regeneration effluents.

The energy balance in Table 8 shows that the biggest loss is due to the latent heat of water in the effluents. It is difficult to recover this heat because it has to be recovered at very low temperatures, lower than the ambient temperature.

In (kW)		Out (kW)		%
NG, LHV	178.29	H_2, LHV	147.54	81.3%
NG+Air Sensible Heat	0.06	Total, Sensible Heat	7.37	4.1%
Power Input	3.04	Bed Loss	2.62	1.4%
		Condenser	4.22	2.3%
		PSA Compressor	0.00	0.0%
		Others, LHV	0.19	0.1%
		Water Latent Heat	19.45	10.7%
Total, In	181.39	Total, Out	181.39	100.0%
Efficiency	81.4%			

Table 8: Energy balance for high pressure reforming + PSA

Low Pressure Reforming with PSA

In integrating low pressure reforming with PSA, reforming is carried out at low pressures but an additional reformate compressor is used before the PSA. S/C ratio of 3 is used in the low pressure scenario. The reforming pressure and PSA operating pressure were assumed to be 1.2 bar and 7.7 bar, respectively. The PSA hydrogen recovery was about 77.4%. Summary of the thermal efficiency analysis is shown in Table 7.

NG Feed	0.8	kmol/hr
NG Fuel	0.038	kmol/hr
NG Total	0.838	kmol/hr
Total Power	7.639	kW
NG Feed compressor	0.132	kW
H_2O Pump	0.000	kW
Air Compressor	1.253	kW
NG Fuel Compressor	0.007	kW
PSA compressor	6.248	kW
H_2 Production	2.254	kmol/hr
Thermal Efficiency (LHV)	77.9%	

Table 9: Thermal efficiency analysis of low pressure reforming + PSA

Table 10 shows the energy balance for the low pressure reforming with PSA system. Most energy inputs and outputs are similar to those in the high pressure system except for the reformate compressor. Also in this low pressure scenario, the stream after the PSA compressor has to be cooled before the PSA. Table 10 shows that the energy loss associated with the PSA compressor is a significant energy loss in the system, and explains the efficiency difference between the high pressure and low pressure system.

In (kW)		Out (kW)		%
NG, LHV	186.76	H_2, LHV	151.42	77.9%
NG+Air Sensible Heat	0.06	Total, Sensible Heat	2.86	1.5%
Power Input	7.64	Bed Loss	2.62	1.3%
		Condenser	7.98	4.1%
		PSA Compressor	7.87	4.0%
		Others, LHV	0.50	0.3%
		Water Latent Heat	21.22	10.9%
Total, In	194.46	Total, Out	194.46	100.0%
Efficiency	77.9%			

Table 10: Energy balance for low pressure reforming + PSA

When the SSR system is integrated with a PSA, the CH_4 conversion is not as crucial as in non-PSA systems, because any unconverted CH_4 in the PSA off gas will be recovered and used for combustion and regeneration. In addition, H_2 in the off-gas can significantly reduce the light-off temperature, which is critical for catalytic oxidation.

Subtask 4.3: Finalize Reformer Design Guide

As detailed in the process modeling work, we chose the combustion gas regeneration approach for our detailed engineering study. Most of the work described in the process modeling was theoretical in nature. In the design guide, we updated the process simulation model to include effect of less than ideal conditions, such as practical exhaust temperatures. Figure 90 represents the reduction in thermal efficiency due to practical limitations in the system design.

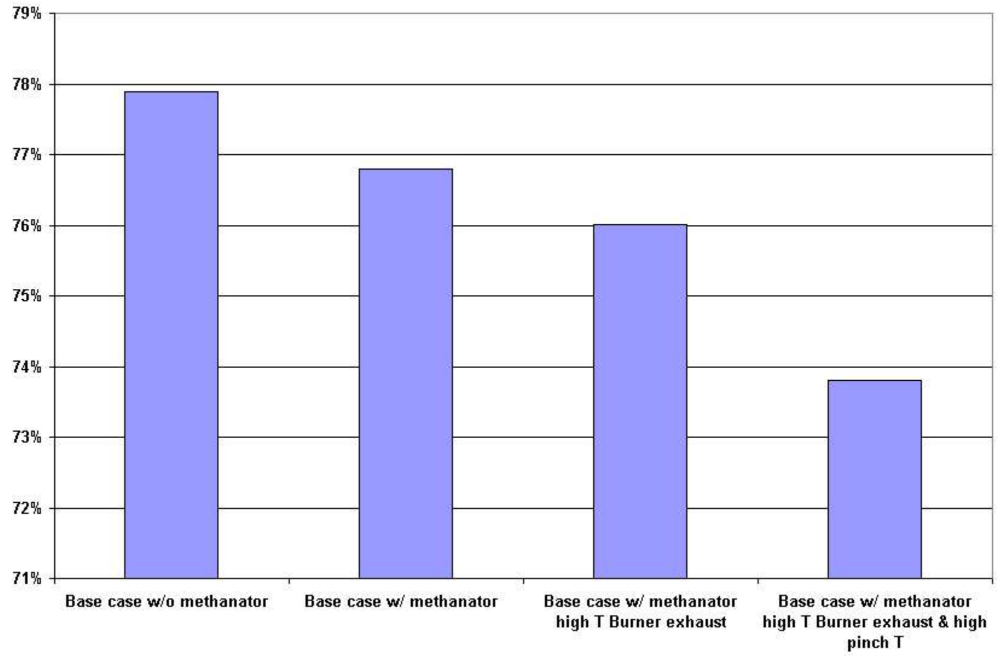


Figure 90: Effect of practical limitations on thermal efficiency

The base case was modeled without methanator and was assumed to have the same conditions as that detailed in Table 1 for combustion regeneration case. This scenario assumed that the reformate and burner exhaust can be cooled to 68°C and 78°C respectively. The second case included the effect of adding methanator to the base case. A more practical and higher combustion exhaust temperature of 121°C was assumed in the third case. The fourth case reflects the effect of increased HX3 pinch temperature, 50 C instead of 25 C, on thermal efficiency.

We also studied the magnitude of different components that determine the system efficiency by creating the energy balance table. Table 11 represents the energy balance for the system for the fourth case in Figure 90, with an estimate for reactor heat loss.

In (kW)		Out (kW)		%
NG, LHV	233.00	H_2, LHV	158.37	65.0%
NG+Air Sensible Heat	0.05	Others, LHV	18.41	7.6%
Power Input	10.71	Bed Heat Loss	8.18	3.4%
		Reform Burner Exhaust	9.22	3.4%
		Reformate	19.94	8.2%
		Regen Burner Exhaust	29.40	12.1%
Total, In	243.76	Total, Out	252.31	100.0%
Thermal Efficiency	73.8%			
Net Efficiency	70.3%			

Table 11: Energy balance of a single reactor system with reactor heat loss

As shown in Table 11, the total energy into the system is made up of LHV of natural gas, electrical power consumption and small sensible heat contribution from the inlet gases. The LHV of natural gas includes all natural gas inputs, including process feed, reforming burner and regeneration feed. The power consumption is due to the air blower/compressor for the reforming and regeneration burners. The sensible heat of inlet gases is the small amount of heat contained in the feed streams as compared to its reference state.

As expected, LHV of hydrogen is the largest percentage of the energy output in the reformate. LHV of unconverted CH_4 in the reformate is about 7.3% of the total energy input. This part of energy can be recycled and will reduce the total energy input, such as in a fuel cell application where anode gas can be recycled. The estimated heat loss from the reactor was about 3.7% of total energy input. The bed heat loss term is due to the fact that the bed has to be heated from the reforming temperature (600^{o}C) to the regeneration temperature (850^{o}C), and it was assumed that we do not recover this heat in the reforming step. If we assume that we can recover this energy in the reforming, the efficiency can be increased by 3.2%. In practice, some of this bed sensible heat can be recovered.

The sensible and latent heat content in the outlet streams also caused significant heat losses, as shown in Table 11. Outlet streams included reformer burner exhaust, reformate and regeneration exhaust. Of these three outlet streams, the reforming burner exhaust has the least heat loss due to the relatively small flow rate. The reformate stream heat loss is about 7.9% of the total energy input and is due to relatively large unrecoverable latent heat of water condensation. The regeneration exhaust is the highest single heat loss stream (11.7% of total energy input) in the system. This is due to the large combustion flow required to provide the regeneration heat (including the CO_2 desorption heat and the bed sensible heat) within a small temperature difference across the reactor. The maximum regeneration temperature of 850°C is dictated by the sorbent material. The regeneration exhaust temperature will vary from the reforming temperature (~600°C) to the regeneration temperature (850°C). The average regeneration exhaust temperature determined the minimum combustion gas flow rate necessary to regenerate the bed within a specified time period.

The process flow diagram selected for the detailed engineering study is presented in Figure 91.

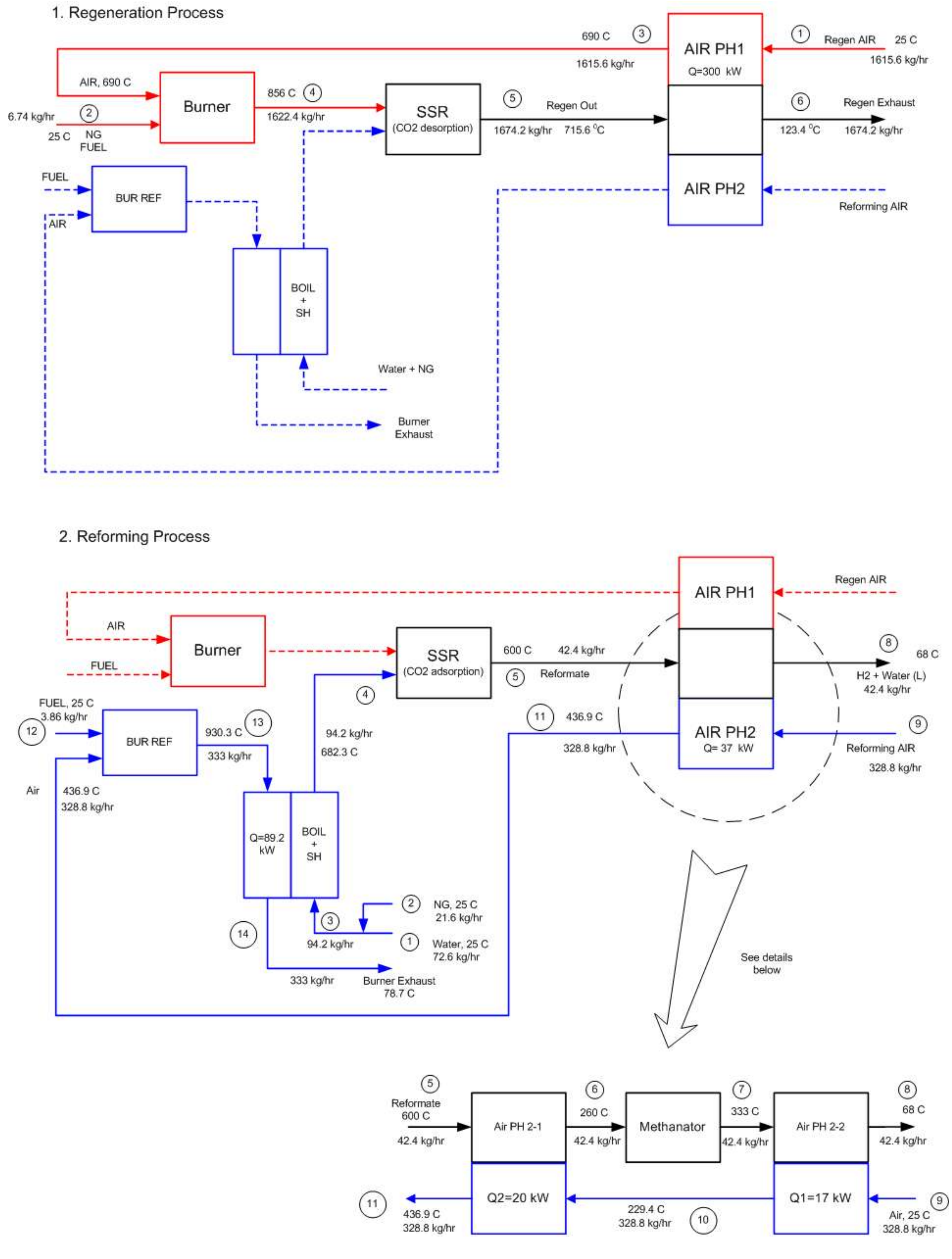


Figure 91: Process flow diagram for detailed engineering study

The heat and material balance of the regeneration and reforming steps are provided in Table 12 and 13 respectively.

Node	1	2	3	4	5	6
Stream	RGAir	RGNGFuel	RGAir2	BurnerOut	RegenOut	RegenExhaust
Flow rates (kmol/hr)						
H2	0	0	0	0	0	0
H2O	0	0	0	0.8232	0.84	0.84
CO2	0	0	0	0.4116	1.5988	1.5988
CO	0	0	0	0	0	0
CH4	0	0.42	0	0.0084	0	0
O2	11.76	0	11.76	10.9368	10.92	10.92
N2	44.24	0	44.24	44.24	44.24	44.24
Total (kmol/hr)	56	0.42	56	56.42	57.60	57.60
Total (kg/hr)	1615.62	3.369	1615.62	1622.36	1674.24	1674.24
Temperature, C	25	25	689.7	855.6	715.6	123.4
Pressure, bar	1	1	1.4	1	1	1

Table 12: Node array for 100 kW reactor system during regeneration

Node	8	9	10	11	12	13	14
Stream	Reformate	Air	Air2	Air3	NGFuel	BurnerOut	BurnerExhaust
Flow rates (kmol/hr)							
H2	4.7152	0	0	0	0	0	0
H2O	1.6744	0	0	0	0	0.494	0.494
CO2	0	0	0	0	0	0.247	0.247
CO	0	0	0	0	0	0	1
CH4	0.1652	0	0	0	0.252	0.005	0.005
O2	0	2.394	2.394	2.394	0	1.9	1.9
N2	0	9.006	9.006	9.006	0	9.006	9.006
Total (kmol/hr)	6.555	11.400	11.400	11.400	0.252	11.652	12.652
Total (kg/hr)	42.319	328.895	328.895	328.895	4.043	332.937	332.937
Temperature, C	68	25	229.4	436.9	25	930.3	78.7
Pressure, bar	1.2	1	1.2	1.2	1	1	1

Table 13: Node array for 100 kW reactor system during reforming

Process flow diagram presented in Figure 91 was used to generate P&ID alternatives for the system. The alternatives were evaluated based on safe and reliable operation, efficiency, capital cost and complexity of operation. Preliminary hazard analysis was conducted to determine the safety and reliability of the alternatives. As a result of our trade-off study, we chose the P&ID with a single reactor system sized for a 100 kW instantaneous output.

The single reactor system was designed to produce hydrogen (reforming) for 1 hour and to undergo regeneration in slightly less than 1 hour. This system, in practice, will work in conjunction with a hydrogen storage device to make it a continuous process. For our design, we chose 2 hour cycle for reforming and regeneration, i.e. 1 hour of reforming followed by approx. 1 hour of regeneration. The choice of 2 hour cycle time was driven by choice of metallurgy in the system and its durability to handle the temperature cycling associated with the process. We also believe that 2 hour cycle provides enough time to overcome transients due to thermal mass of the system.

Subtask 4.4: Reformer Design and Cost Estimates

We worked with an engineering firm, Zeton Inc, to perform the detailed engineering study and prepare the cost estimate for a 50 kW reformer system. As part of the study, first we developed an overall operating philosophy for the system including start-up, planned shutdown and emergency shutdown. The control parameters and required flexibility in operation were also defined. This led to identification of required balance of plant components.

The heat and material balance of the system was used to generate design basis for heat exchangers in the system (Appendix I). The reactor design was developed based on 1 kW reactor performance and process simulation results. The reactor design was in accordance with ASME VIII Div I. Detailed specification sheet and drawing of the reactor is provided in Appendix J. Zeton estimated the system piping requirements taking into the operating temperature, thermal stress and thermal cycling requirements. The material selection for system components including the piping are presented in Appendix K.

Pressure drop budget for components was determined by performing trade-off studies between pressure drop and equipment size/cost (Appendix L). This determined the overall operating pressure for the system. Detailed specification sheets were generated for system components

(Appendix M). Detailed P&ID of the system is provided in Appendix N. Zeton obtained price quotes for these major components from multiple vendors. Zeton also provided a lump sum price quote for the system based on fixed price quotes on the major components (Appendix O).

We estimated the heat loss through the system components including reactor, heat exchangers and piping. This heat loss estimate was included in the process simulation to calculate the effect on system thermal efficiency. Figure 92 shows the effect of heat loss in the thermal efficiency of the system. It is evident that heat loss significantly reduces the thermal efficiency of the system.

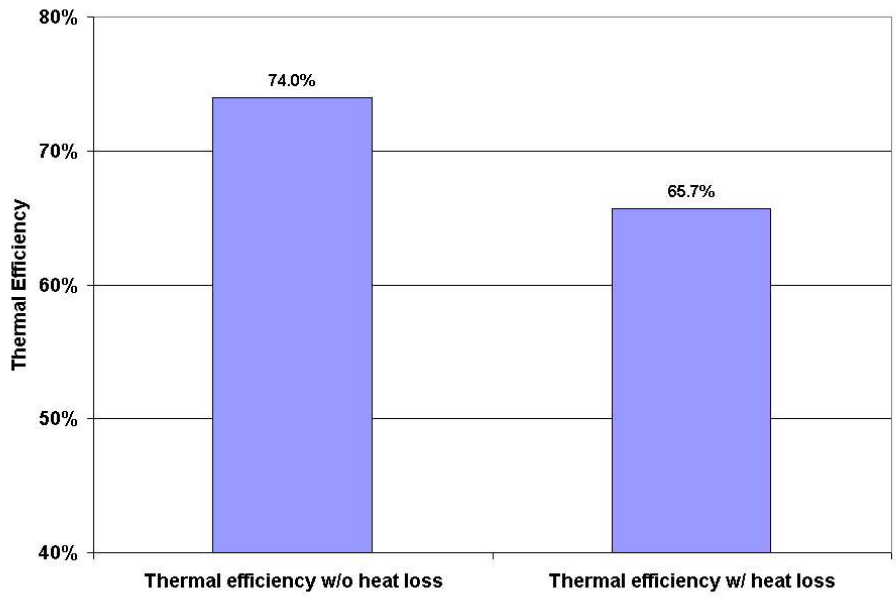


Figure 92: Effect of heat loss on thermal efficiency of the system

The pressure drop through the system determines the discharge pressure required for the air compressor used during combustion gas regeneration. The high system pressure drop and high air flow rate increases the parasitic power due to the air compressor and results in low net efficiency. Figure 93 shows net efficiency as compared to the thermal efficiency of the system.

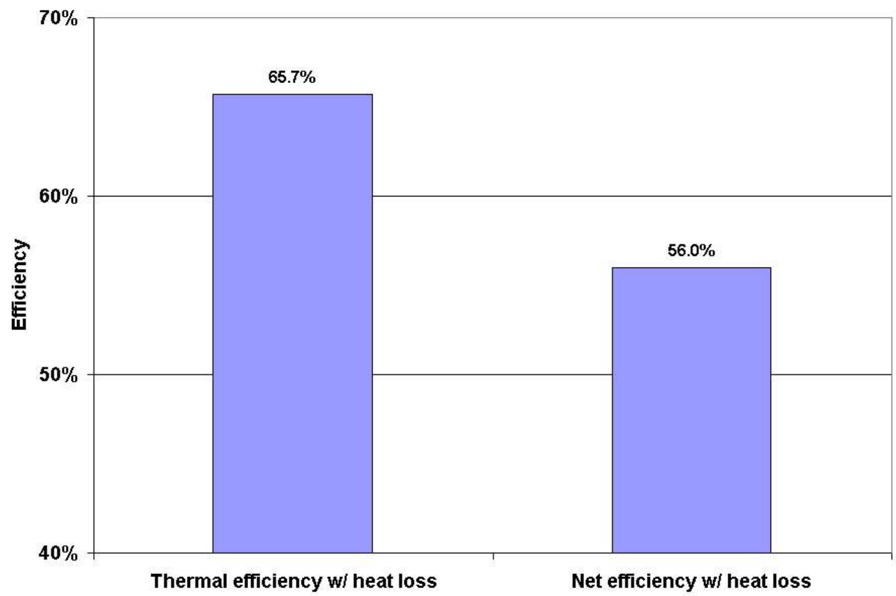


Figure 93: Comparison of thermal and net efficiency

As a way to improve the thermal efficiency, we investigated a two bed system to recover more heat in the system. Figure 94 shows a possible two-reactor integrated system.

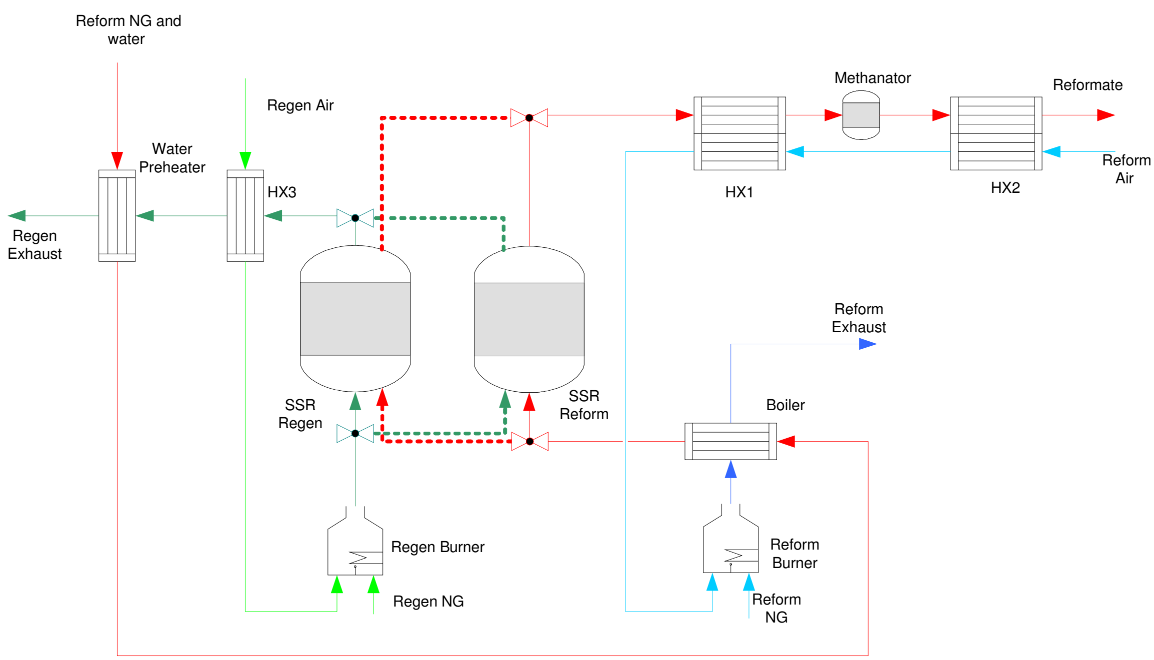


Figure 94: Combustion-gas regeneration two-reactor SSR system

The advantage of two reactor integrated system is their water and natural gas preheater that allows better heat recovery from the regeneration exhaust stream. It can also produce H_2 continuously. This system, however, requires high temperature valves to switch between the reforming and the regeneration mode, which leads to higher capital and operating costs. The thermal efficiency improvement in a two bed system as compared to a single bed system is presented in Figure 95.

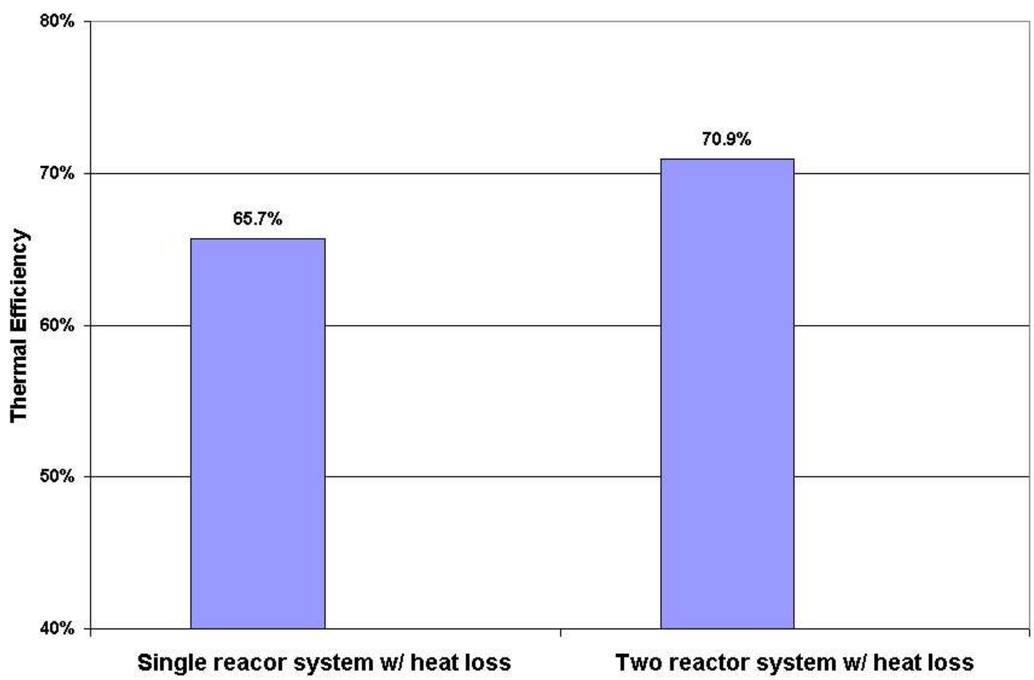


Figure 95: Modular and two-reactor system efficiency

As shown in Figure 95, the thermal efficiency of the process can be improved by using a two bed system but still is lower than our target of 78%. The two bed system still has the problem of lower net efficiency due to high parasitic power.

Conclusion

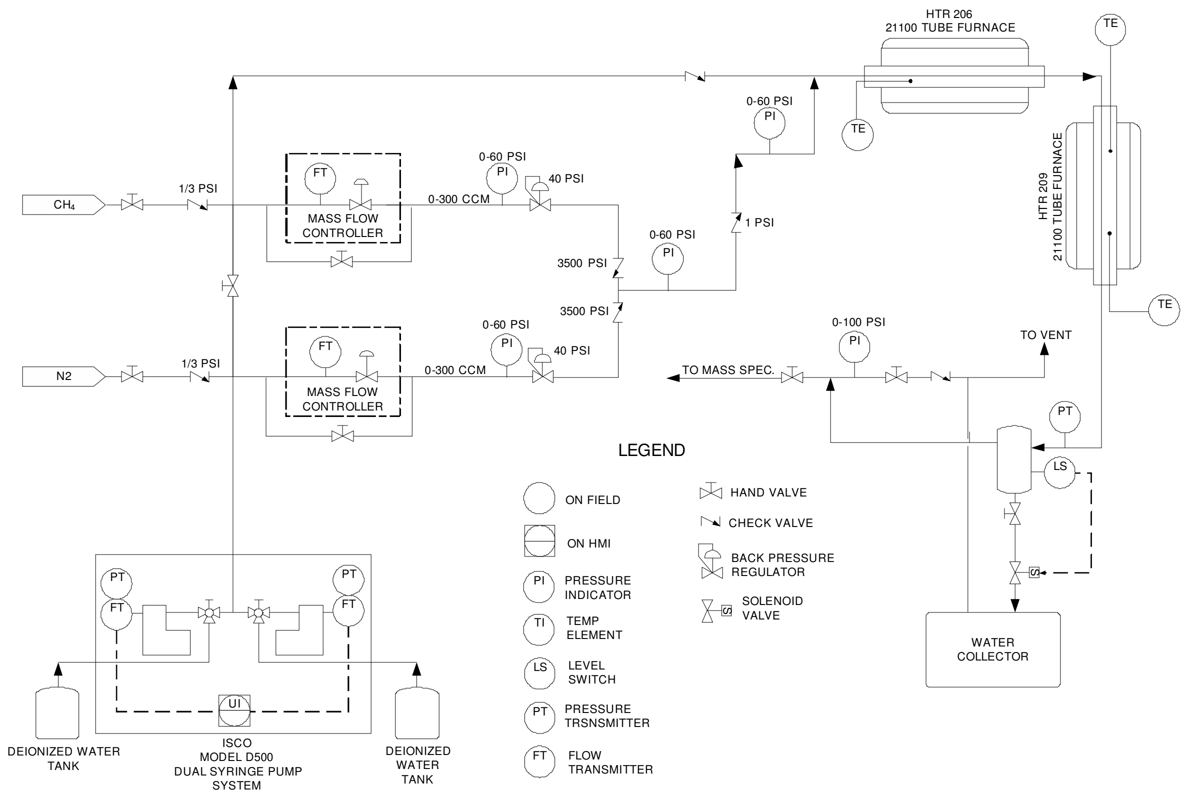
The predicted thermal efficiency of the system is lower than the 78% target for go/no-go criteria for the project. We communicated our findings to the DOE project manager and they concurred in our decision to not proceed with the 50 kW reformer system.

Task 5: Reactor Design and Construction

Subtask 5.1: First Reactor Design Cycle

Micro-reactor System Description

The micro-reactors were developed to test catalysts that requiring many AER cycles under different reforming temperatures, flow rates, S/C, and regeneration conditions. The process flow diagram for the Micro-reactor test stand is shown in Schematic 1. The experimental set up includes a gas and deionized water delivery system, a pre-heater, a fixed-bed reactor, water-gas separation, NI control system, and a magnetic sector mass spectrometer for gas analysis. The feed gases pass through the pre-heater into the reactor. In the reactor, the pre-heated feed stream passes over the packed catalyst/sorbent bed. For all 2004 & 2005 tests reported, 32.5 cc of CSMP sorbent material and 7.5 cc of a commercially available 0.5% Rh on alumina (Engelhard Escat 326) were used.

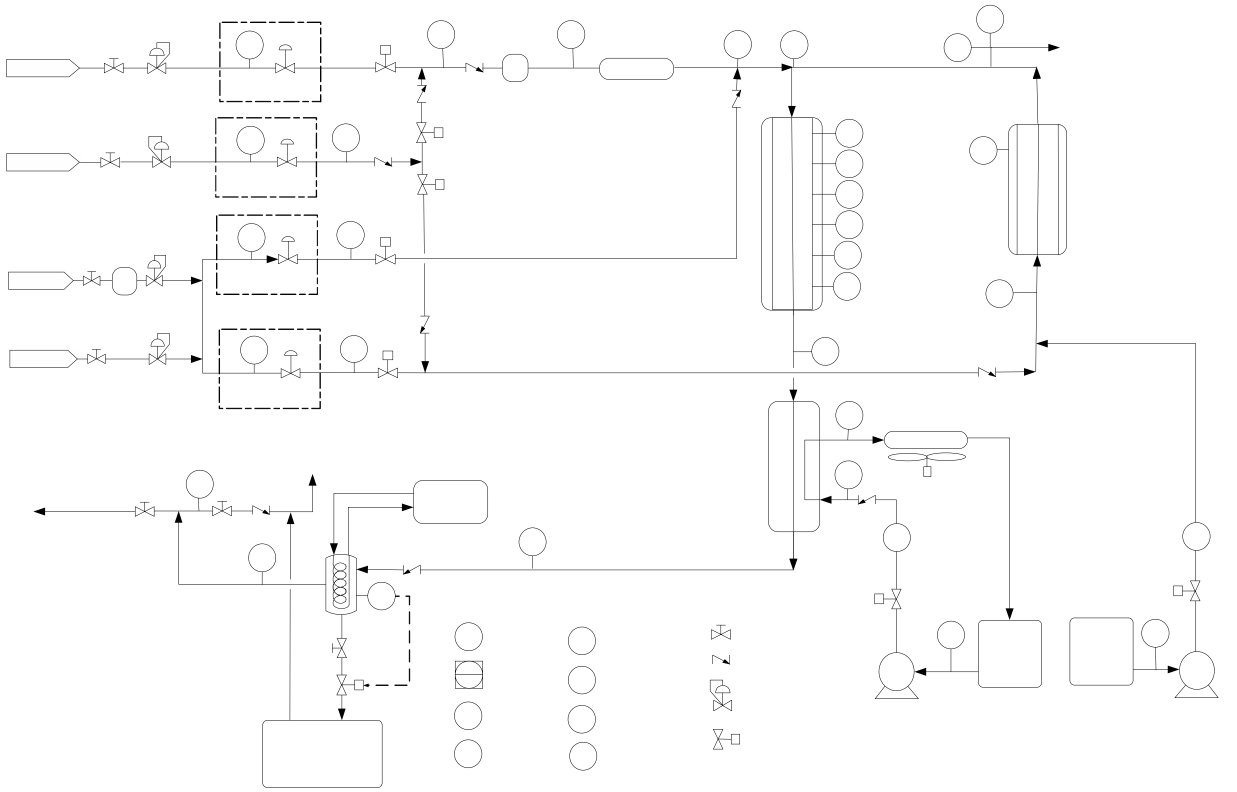


Schematic 1: The process flow diagram of the experimental set up

After exiting the reactor the reformate passes into a knockout vessel used to separate condensed water from reformate. All gas analyses are reported in mole percent on a dry gas basis. Pressure, temperature and flow rate data collected via LabVIEW are combined with mass spec analysis to calculate reaction efficiencies found in Appendix B.

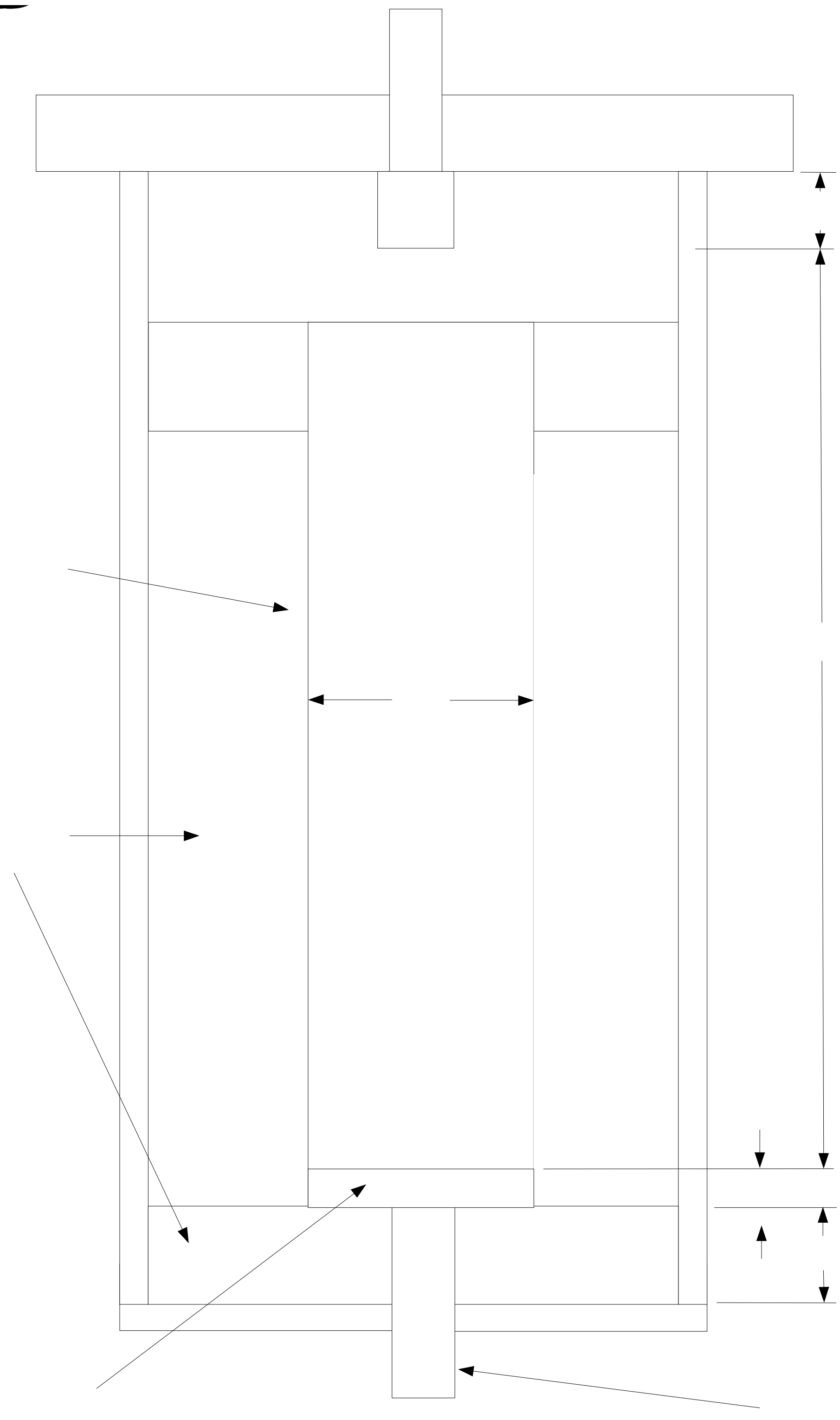
AutoSSR 1kW System Description

The AutoSSR 1kW reactor combines SMR, water-gas shift, and purification into one reactor to produce high purity hydrogen. Similar to the micro-reactor configuration, the distinct parts of the process included the gas delivery, steam production; AER and regeneration reactor, gas-water separation and hydrogen concentration analysis shown in the Figure below.



Schematic 2: The process flow diagram for the AutoSSR 1 kW Unit (Top Down) - Bay 54

The natural gas feed was conditioned through a sulfur trap to remove unwanted sulfur odorants. The reactor was vertically mounted with downward flow. Electrical heating tapes were used to minimize heat loss through the piping and tubing in the system. Pressure relief valves were also installed to prevent any pressure build-up above the specified maximum operating pressure. The flow of only steam (0-18 ml/min H20) or a combination of steam and natural gas (0-8 SLPM) were controlled to react with select catalyst. The control system alternated AER and regeneration conditions primarily through cycling of furnace temperatures between 600ºC -800ºC, the cycling of a NG mass-flow meter on and off while changing water pump flow rates. The unit was designed to run continuously. The control system also monitored key thermocouple signals, level switch activity, flow sensors and pressure transducers to perform a safe shut-down if necessary.



Schematic 3: The AutoSSR 1 kW reactor design - Bay 54

In the above design, the reactor shell was made of 6” SCH 40 carbon steel pipe. The flange was Class 150 Type 316SS and the vessel was designed according to ANSI B31.3. The vessel was designed to operate at maximum temperature of 850°C and 14.9 psig. Multi-layered ceramic paper insulation (1/8” 714H – *Unifrax Corp*) was wrapped around an alumina sleeve used as internal insulation to prevent heat loss and protect carbon steel shell from exposure to high temperature. The flange also has thermocouple ports to measure the vertical temperature profile in the reactor.

There were two independent mass flow controllers to deliver natural gas for regeneration and AER. Regeneration was achieved by combining air preheated through a combustion heater to 400ºC with natural gas. The hot gases were passed over the packed catalyst/sorbent bed to facilitate catalytic combustion with a subsequent rise in temperature. The temperature increase propagated through the catalyst bed until the catalyst bed reaches 800ºC. The process continued until carbon dioxide was completely liberated. To reduce start-up time, steam was introduced to help raise the bed temperature to >350°C to achieve light-off.

To ensure safe operation of the unit, it was necessary to stay below the lower flammability limit (LFL) at any given temperature. The LFL is the percentage by volume of fuel, in fuel-oxidant mixture, above which flame propagation can be sustained. LFL decreases with increasing temperature. The safety set included a shutdown based on the LFL.

Certain fuel to air ratio was necessary to achieve the desired adiabatic temperature in the combustion process. This ratio is dependent on inlet temperature of the fuel-air mixture and the amount of dilution N2 and steam. The following equation was used to determine the air flow rate to control combustion temperature based on the natural gas feed rate. The methane combustion efficiency selected was 1.0 to stay below the maximum operating temperature.

$$\boxed{y=1.05\left[(24209.7+0.145436\,T_2)\frac{x}{T_2-T_1}-2.165235\,x-0.986204\,z-1.54681\,w\right]}$$

Where:

y: air flow rate, slpm.
x: methane flow rate, slpm.

: methane combustion efficiency (eg, 0.85).
z: N_2 flow rate, slpm.
w: water flow rate, g/m.
T_1: Preheater temperature, C.
T_2: Desired combustion temperature, C.

Once the bed was fully regenerated, the air and natural gas solenoids closed. Six purge volumes of inert gas (steam and/or N2) passed through the reactor before beginning the AER cycle. At

this point, the natural gas was diverted from the combustion line to the reforming line by activating and deactivating the appropriate solenoids. Natural gas combined with steam, flowed through the pre-heater raising the gas temperature to the optimum reforming temperature. As the feed stream passed over the catalyst bed, the AER reaction proceeded resulting in a stream of high purity H2 with inconsequential levels of CH4, CO and CO2. As the sorbent reached saturation, concentrations of CO2 increased. CH4 slip increased and H2 concentrations fell. When the percent H2 dropped below 90% of the gas composition, the natural gas feed was cut off. Six purge volumes of inert gas were swept through the reactor to complete the cycle.

After exiting the reactor, reformate, combustion, or purge gases passed through the water cooled heat exchanger to cool the system exhaust gases. A chiller was used to further cool the exhaust gas and a knock-out vessel was used to collect the condensed water. Reformate was discharged into a ventilation hood. A slip stream of the product gas was continuously monitored by a magnetic sector mass spectrometer (mass spec) for detailed dry gas compositional analysis. All gas analyses were reported in mole percent on a dry gas basis. Pressure, temperature and flow rate data collected via LabVIEW were combined with mass spec analysis to calculate reaction efficiencies.

Subtask 5.2: First 1 kW Reactor Fabrication

The two micro-reactors were fabricated as per above design.

The first 1 kW reactor was fabricated as per above design.

Subtask 5.3: First Reactor Installation

Micro-reactor Installation

The two micro-reactors were installed into two independent test stands separated the by NI Control hardware in a NEMA enclosure. The control software allowed for 24/7 operation. The reactor was a ¾ inch stainless steal reactor with a 0.049” wall thickness. The reactor was vertically mounted with downward flow. The catalyst sorbent mixture was supported by quartz wool. The mixed sorbent/catalyst was loaded in the reactor and packed to a 7.3” bed length with a length/diameter (L/D) of 11. The reactor was placed in the furnace with the catalyst bed situated in the active heat zone. The inlet Type K thermocouple (TCin) measured the preheated gas before the sorbent bed. The outlet Type K thermocouple (TCout) controlled the furnace temperature. Brooks 5850i mass flow controllers were used to deliver methane and nitrogen. Water was metered through an ISCO dual syringe pump.

Pressure transducers, flow indicators, pressure gauges, and thermocouples were used to monitor the process. A 1/3 PSIG check valve on the vent line prevented pressure build up. A water knock out vessel, equipped with a level switch to automatically drain, collected condensate. The entire reformate gas was ported to the mass spectrometer for gas analysis.

Electricians completed the electrical connections of the electrical control panel to the 110V circuit and connected the process PC and the unit hardware. Hardware calibration and signal processing were completed. A calibration check on all MFCs were checked and verified within the accuracy reported by the manufacturer. The ISCO water pumps were measured for accuracy. The unit was pressure tested. All of the unit hardware was tested including the safety shut-down signals.

AutoSSR 1kW System Installation in Bay 54

The first AutoSSR 1 kW size reactor was installed in an existing test stand (Bay 54) using NI Control hardware and software to allow for 24/7 operation. Brooks 5850i mass-flow controllers were used to control gas flows. Regulators and back-pressure regulators were used to maintain the operating pressure across the mass flow controllers. Thermolyne furnaces equipped with I2R over-temperature protection provided the heat for steam production. An SEC heat exchanger and Modular Cooling System (MCS) were used to cool the system exhaust gases. An additional glycol cooled chiller coil was used to further cool the exhaust gas located in the knockout vessel. In addition, electronically actuated solenoid valves were used as shut-off valves. Pressure transducers, flow indicators, pressure gauges, Type K thermocouples, and a thermal conductivity detector were used to monitor the process. A burst disk prevented pressure build up beyond the operating envelope maximum operating pressure.

The AutoSSR 1 kW unit was contained in Bay 54 complete with a vented canopy allowing for a minimum of 6 air changes/hr of air flow. The canopy was equipped with a combustible sensor to alarm at 20% LEL and drop all electrical power to the canopy if the sensor measured 40% of the lower explosion limit (LEL). The control equipment was also located within the bay. The user interface for control was located outside of the bay, near the unit.

Electricians completed the electrical connections of the electrical control panel to the 240V circuit and connected the process PC and the unit hardware. Hardware calibration and signal processing were completed. A calibration check on all MFCs were checked and verified within the accuracy reported by the manufacturer. The piston FMI water pump was calibrated and found to oscillate. Flow indicator, FL 58, was outputting oscillating signal due to the piston pump operation. The oscillation was corrected. The unit was pressure tested. All of the unit hardware was tested including the safety shut-down signals.

The Honeywell Thermal Conductivity detector (TCD) was initially used to control signals for the process. The Honeywell TCD was calibrated at the factory using air (Conductivity, K, of 1.0) as a background or zero gas and Hydrogen (K, 6.803) as the span gas. Auxiliary gas analysis was performed using the Prima dB on-line process mass spectrometer. The Honeywell TCD was later disconnected.

Subtask 5.4: Second 1 kW Reactor Design

The second 1 kW reactor was designed with a metal fiber burner (MFB) combustion system for regeneration. MFB is similar to conventional burner in its flame type combustion. However, the flame in the MFB is held to its surface and hence, allows for a compact design. A cross-section of the schematic is presented in Figure 96.

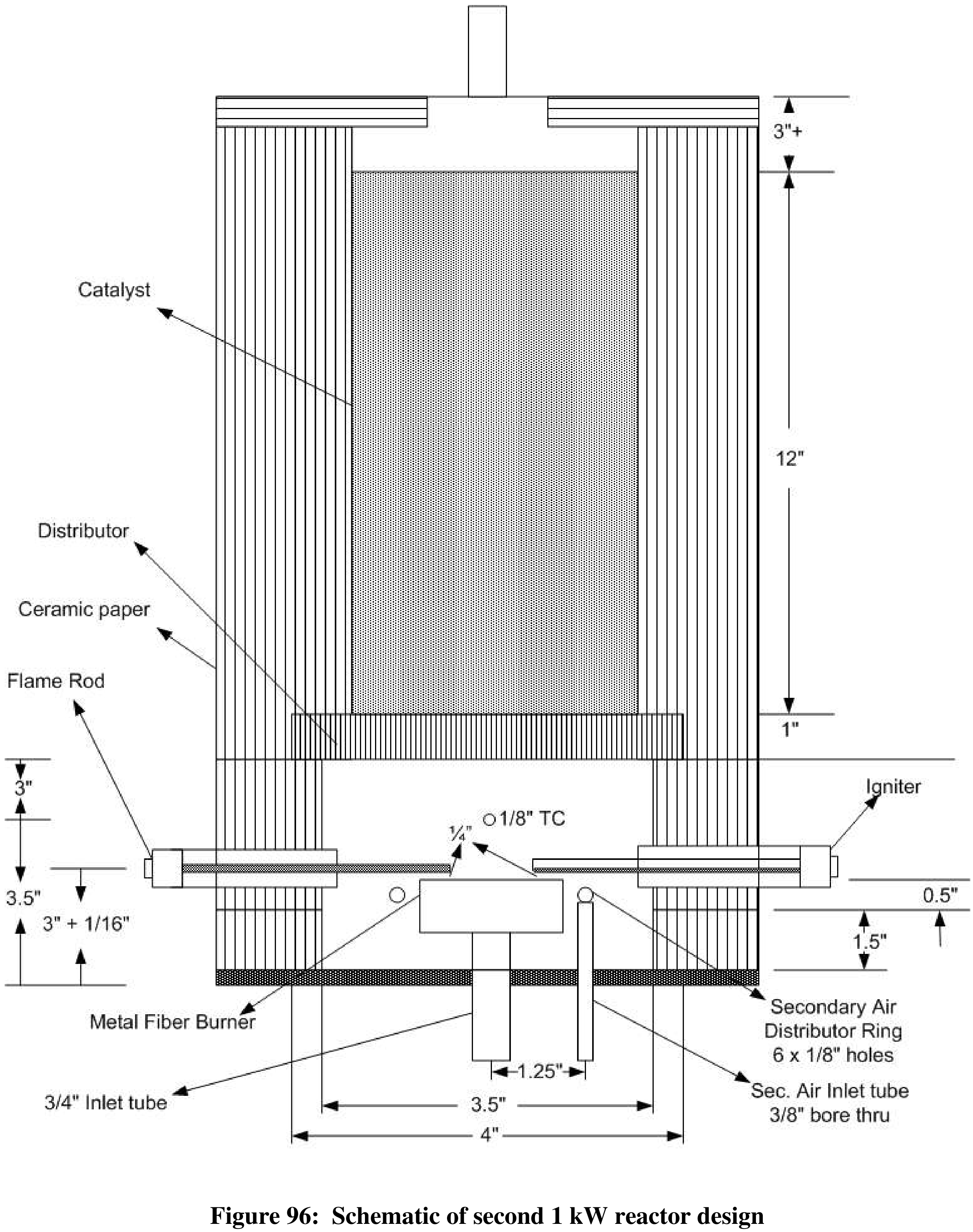


Figure 96: Schematic of second 1 kW reactor design

In the above design, the reactor shell was made of 6" SCH 40 carbon steel pipe. The flange (not shown in the schematic) was Class 150 Type 316SS and the vessel was designed according to ANSI B31.3. The vessel was designed to operate at maximum temperature of 850 C and 14.9 psig. Multi-layered ceramic paper insulation (1/8" 714H – *Unifrax Corp*) was used as internal insulation to prevent heat loss and protect carbon steel shell from exposure to high temperature.

Metal fiber burner (*Bekaert*) was custom designed to fit the reactor profile and burner power requirements. The metal fiber burner has the ability to combust at 20% excess air ratios. However, our regeneration temperature required 300% excess air. The excess air for combustion was introduced using a secondary air distribution ring. The distribution ring was made of Inconel tubing and had perforation pattern on its face to ensure uniform flow distribution. The inside diameter of the distribution ring was designed to fit outside of the metal fiber burner. The top face of the ring was held at the same level as that of the top face of the MFB. This design ensures good mixing of combustion exhaust and secondary air. During reforming step, the secondary air distribution ring was used to introduce fuel and steam into the reactor.

The design also included a spark igniter and a flame rod (*US ignition)*. As the name suggests, the spark igniter was used for combustion light-off. The flame rod provided feedback on the combustion by detecting the flame. The spark igniter and the flame rod were installed through 1" tube sections welded to the side of the reactor shell. The 1" tube sections were designed to be welded such that the tip of the igniter and the flame rod are ¼"- ½" vertically separated from the surface of the metal fiber burner.

A thermocouple port was designed to measure the combustion temperature. The flange also has thermocouple ports to measure the vertical temperature profile in the reactor. A distributor (1" Zirconia stabilized Alumina - *Vesuvius HiTech Ceramics*) is used in the reactor to create good mixing of combustion exhaust and secondary air. The distributor also functions as a physical support for the catalyst/sorbent bed. The distributor is, in turn, supported by the internal insulation of the reactor. This ceramic distributor also acts as a flame diffuser, if there is any flame lift-off during any upset conditions.

Subtask 5.5: Second 1 kW Reactor Fabrication

The second 1 kW reactor was fabricated as per above design.

Subtask 5.6: Second 1 kW Reactor Installation

Second 1 kW size reactor was installed in a test bay. Mass flow controllers were used to control gas flow rates. Electronically actuated solenoid valves were used as shut-off valves. A wick boiler in an electrical furnace was used for generating superheated steam. Another electrical furnace was used to heat natural gas and steam mixture to reactor inlet temperature. Electrical heating tapes were used to minimize heat loss through the piping and tubing in the system. Pressure relief valves were also installed to prevent any pressure build-up above the specified maximum operating pressure. Water cooled heat exchangers were used to cool the system exhaust gases. A chiller was used to further cool the exhaust gas and a knock-out vessel was used to collect the condensed water. Detailed P&ID of the test setup is provided in Appendix N.

Real time Fieldpoint® control modules (*National Instruments*) were used for the control system. Labview® was used to write the control code for the test stand. A separate burner control module was installed to light-off and monitor the MFB. The igniter and the flame rod are connected to a stand-alone burner control module. A high voltage transformer was used to provide the spark to the igniter. The burner control module interfaces with Labview® to integrate operation of the burner with the overall system.

Subtask 5.7: Five kW Reactor Design

Based on discussions with internal reactor design experts and an outside engineering firm, we learned that the 5 kW reactor will not provide us with any significant new information about the system as compared to the 1 kW reactor. The scale-up issues in 100 kW size range will be totally different from that of a 5 kW reactor. After discussions with DOE manager, we decided not to pursue the 5 kW reactor.

Subtask 5.8: Five kW Reactor Fabrication

5 kW size reactor was not fabricated for reasons described in subtask 5.7.

Subtask 5.9: Five kW Reactor Installation

5 kW size reactor was not installed for reasons described in subtask 5.7.

Task 6: Reactor Testing

Subtask 6.1: First Test Stand Modification and HAZOP

A Hazard and Operability Study (HAZOP) was performed on the Chevron Technology Ventures CSMP Automated SSR 1 kW Reactor according to AIChE guidelines. This qualitative study was conducted on July 30, 2003, with the HAZOP technique utilizing a team approach to identify potential hazards and to investigate the underlying causes of potential operational deviations. These HAZOP analyses are routine and are required under the detailed “Management of Change” process used by Chevron to ensure safe operation. The HAZOP was a multidiscipline six person team to review Process Engineering, EH&S, Codes and Standards, and Electrical design.

The areas of the test stand to be included in this HAZOP were subdivided into workable sections called "nodes" for a detailed review using the prescribed HAZOP criteria. As part of this identification, possible consequences of potential hazards were noted, as well as safeguards in place, which would mitigate and/or control the circumstance. The team members identified a total of 36 recommendations pertaining to safety, and operability concerns. Those recommendations were accepted and implemented according to an action plan. A detailed Laboratory Standard Operating Procedure (LSOP) binder containing the P&ID schematics, electrical drawings, Lock-out Tag-out, Operating Envelope, Reactor Loading, Start-Up, Shut-down, & Operating procedures and Safety Shut-down events for each unit was compiled. The binders were located lab near each bay for easy reference.

Subtask 6.2: Microreactor and First AutoSSR 1 kW Tests

Microreactor Tests

Materials

Experiments were conducted to examine the effects of material composition, post-processing conditions, temperature, steam to carbon ratios, and other operating parameters under AER conditions. Materials meeting the required CO2 sorption capacity and stability would be recommended for scale up for the 50 kW fuel processor. Thermogravimetric Analysis (TGA) was the selection criteria to optimize the composition for scale up. Based on TGA data, a series of materials was tested in the micro-reactors to correlate materials TGA performance under reforming conditions. The catalyst inventory included powders, precious metal extrudate compositions, sorbents, steam methane reforming (SMR) catalysts, and integrated materials (sorbent and SMR catalyst) prepared by CSMP and extruded both at ETC's Catalyst Group (RTC) in Richmond, CA and CSMP in Albuquerque.

In 2005, the powders were extruded and post processed at the new CSMP facility (Appendix A). Parent powders were mixed by either by hand or by machine yielding a 50 gram sample of extrudates. Larger scale samples were prepared by screw extrusion of the parent powder yielding approximately a 900 gram sample of extrudates to test in the 1 kW Fuel Processors.

Experiments were conducted from January 2004 – July 2005 in the micro-reactors under the following conditions:

SMR Catalyst	Commercial Rhodium Catalysts (0.5%Rhodium on Alumina)
SMR Catalyst Weight, g	4.5g
SMR Catalyst Volume, cc	7.5cc
CSMP CO2 Sorbent Weight	Varied

CSMP CO2 Sorbent Volume, cc	32.5cc
Steam / Carbon	3.0
Carbonation Temperature, °C	600
Calcination Temperature, °C	800
GHSV, hr-1	390

The theoretical maximum sorption capacity of grams of CO2 sorbed per gram of CaO is 79%. Fig. 1 shows a typical response curve for one complete cycle where H2, CH4, N2, CO, and CO2 are plotted over a 2.5 hour period. Initially H2 concentrations are > 95% with CO and CO2 concentrations below 1%. As the CO2 sorption declines, methane slip increases followed by increased CO and lower H2 concentrations in reformate. After reaction proceeds for 60 minutes, the program switches to regeneration. Methane flow is stopped and nitrogen is introduced into the system during regeneration where CO2 is desorbed.

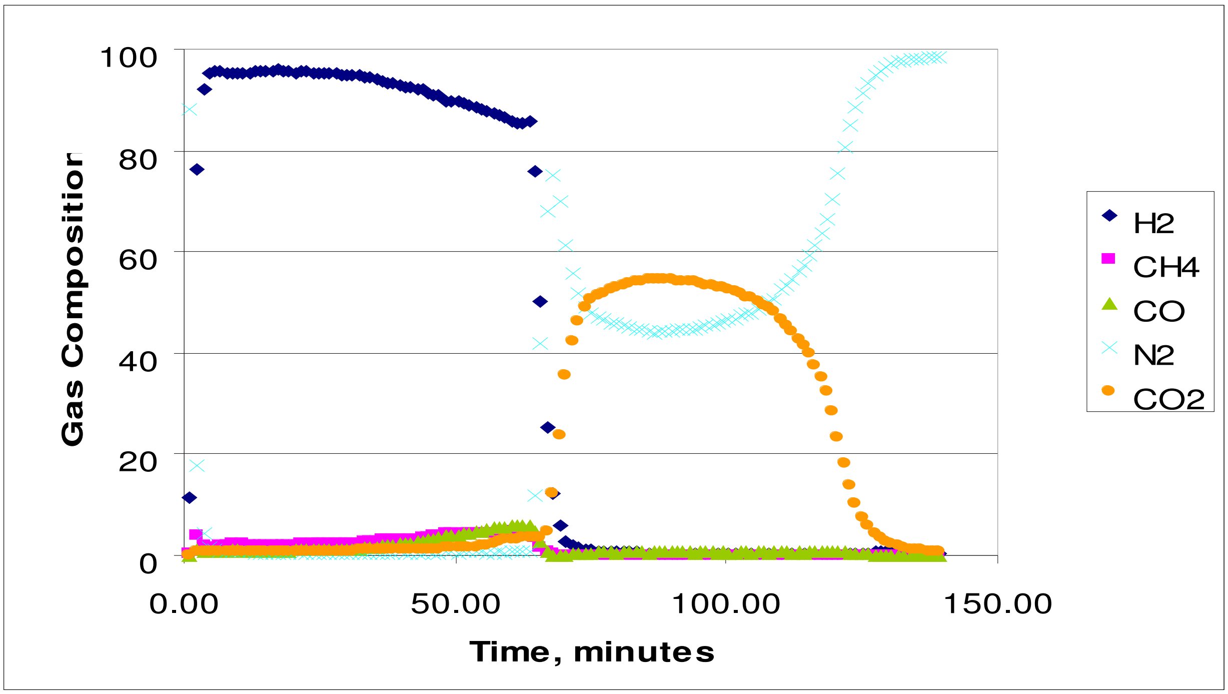


Figure 97: A tpical response curve for one complete cycle where H2, CH4, N2, CO, and CO2 are plotted with respect to time. [S/C-3, GHSV-390 hr-1, TCout-600C, 1 atm]

The reaction efficiencies are calculated for H2 concentrations greater than 90%. During this period H2 content, methane conversion and CO2 sorption are maximized.

Discussion

CSMP materials were initially extruded at RTC. Control of the moisture content of the mix, extrusion rate, and extrusion temperature were the most important variables. Small scale samples were prepared by hand mixing CSMP powders with binder and extruding the material on a die-press. “Large Scale” samples at RTC were prepared by mixing CSMP material with a mechanical mixer and using a single screw extruder yielding 1400 - 1800 gram sample of extrudates to test in the 1 kW Fuel Processors. Prior to extrusion some powders were subjected to high temperatures under controlled conditions at CSMP, designated Post Processing (PP). Selected powders received additional sample preparation prior to extrusion at RTC's facility known as pre-procession extrusion (PPE). All extrudates were then calcined at various temperatures after extrusion (CE).

Small Batch Materials Extruded at RTC

Figure 98 shows the g CO2 Sorbed/g Sorbent for the "Small Batch Materials" plotted as a function of number of cycles. Post processing temperature is a key parameter in sorption capacity and stability. CO2-TGA tests showed the effect of extrudate calcinations temperatures on CO2 sorption negligible. The micro-reactor tests demonstrate the CO2 sorption capacity is improved by post processing and/or calcining the materials at higher temperatures. The Small Batch Materials Table containing the Sample ID, composition, and conditioning for each extrudate is located in Appendix C. Also included in Appendix C are the data tables and graphs of the average reaction efficiencies, gas composition, and CO2 Sorption Capacity for each extrudate tested when H2 > 90%.

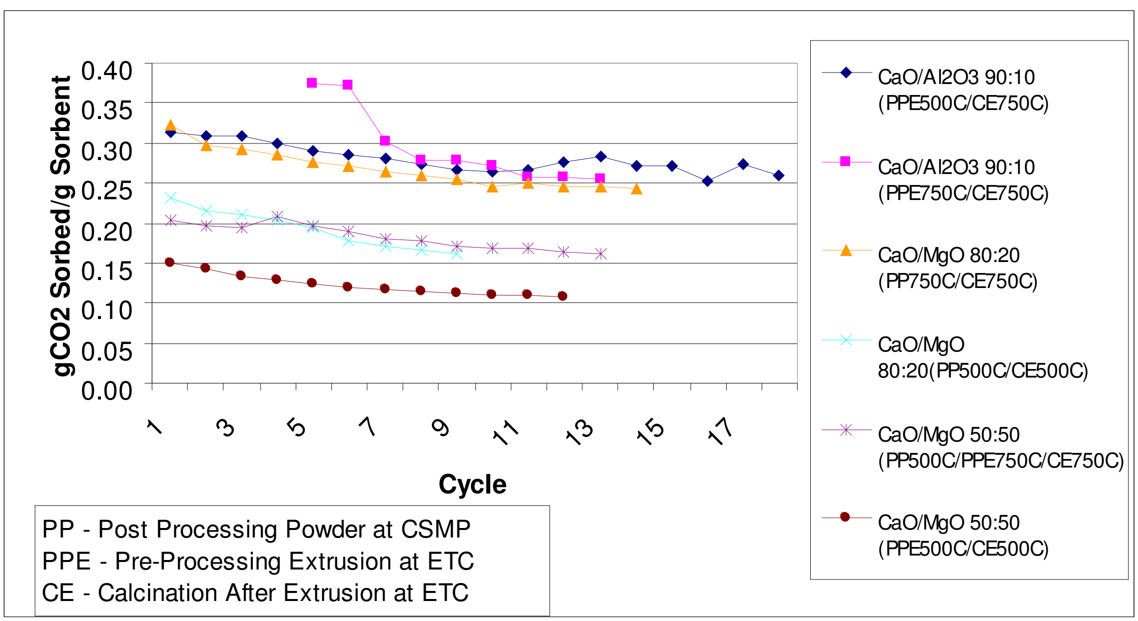


Figure 98: CO2 Sorbent Capacity of the "Small Batch" Materials as a function of number of cycles [S/C-3, GHSV-390 hr 1, TCout-600C, 1atm]

Integrated Function Materials Extruded at RTC

CSMP used a 3 step approach in preparing an integrated SMR with sorbent material for SSR. First the sorbents and reforming catalyst were separately prepared and pelletized. Micro-reactor tests compared the six CSMP SMR catalysts to a commercial rhodium catalyst. Micro-reactors tests demonstrated the CSMP catalyst had better catalyst activity than the commercial catalyst.

Next the CSMP SMR catalyst and sorbents were combined and tested for activity. The sorbent and SMR catalyst were integrated into one particle once the SMR activity in the combined tests were demonstrated. The integrated function materials were composed of 90 Wt% CaO/MgO
(50:50) with 10 Wt% 0.5% Rh/Al2O3. Calcination data was not available. Figure 99 compares the effect of cycles on CO2 sorption capacity in micro-reactor tests for the integrated materials.

The Integrated Function Materials had significantly lower CO2 sorption capacity when compared to an extrudate with a similar composition without the SMR catalyst included in the formulation. Adjusting the sorption capacity for 5 Wt% rhodium in the integrated function materials doesn't account for the poor performance. The lower activity may be due to sintering, the encapsulation of the active metal phase, or the masking of the crystallites due to carbonation. The Integrated Function Materials Table containing the Sample ID, composition, and conditioning for each extrudate is located in Appendix D. Also included in Appendix D are the data tables and graphs of the average reaction efficiencies, gas composition, and CO2 Sorption Capacity for each extrudate tested when H2 > 90%.

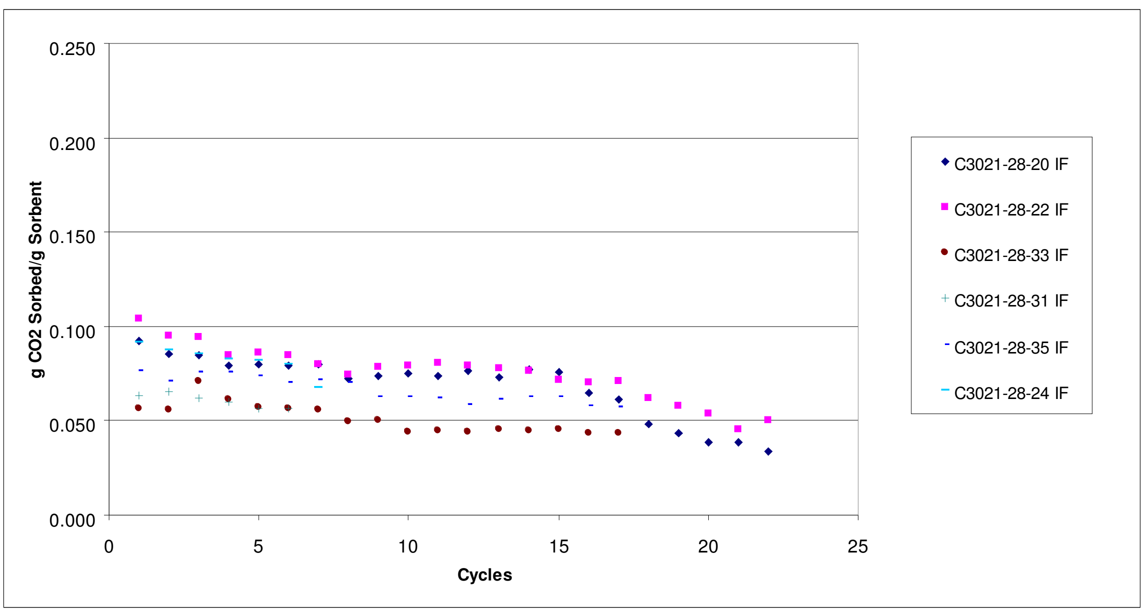


Figure 99: CO2 Sorbent Capacity of the Integrated Materials as a function of number of cycles [S/C-3, GHSV-390 hr 1, TCout-600C, 1 atm]

Scale-Up Materials Extruded at RTC

Evaluation of the "Large Scale" samples extruded by RTC shows the same basic trend as the small batch samples. Figure 100 compares the effect of cycles on CO_2 sorption capacity in micro-reactor tests for the "Large Scale" materials. The difference in the material performance of the same formulation is due to the post processing and calcination history. No large scale samples of a CaO/Al_2O_3 90:10 with 15% Al_2O_3 binder were made for comparison. The Scale-Up Materials Table containing the Sample ID, composition, and conditioning for each extrudate is located in Appendix E. Also included in Appendix E are the data tables and graphs of the average reaction efficiencies, gas composition, and CO_2 Sorption Capacity for each extrudate tested when $H_2 > 90\%$.

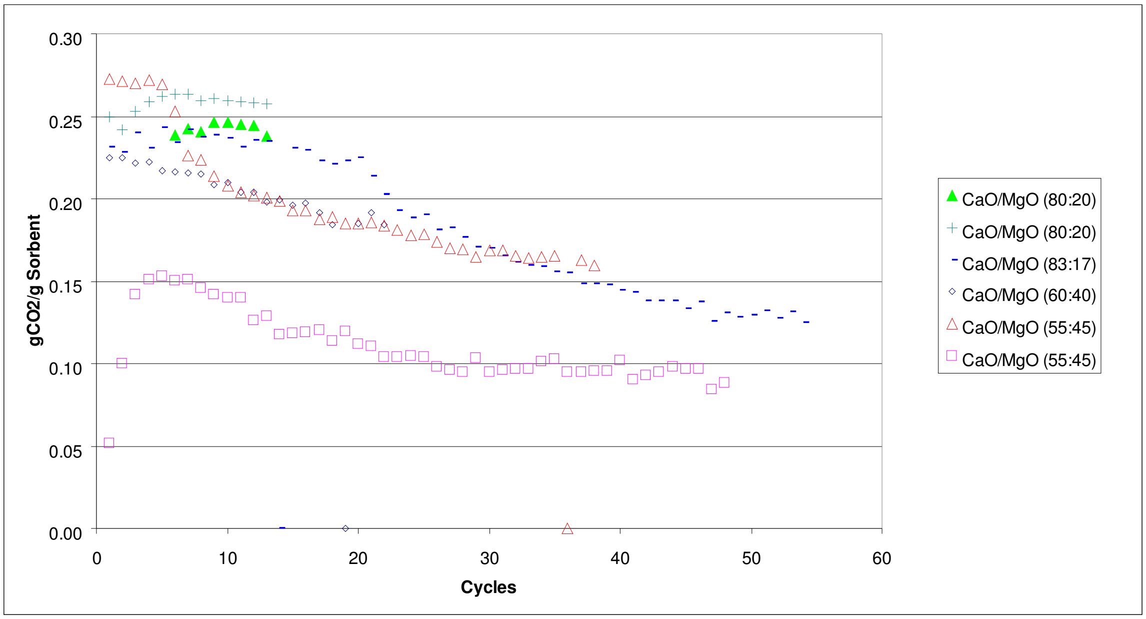


Figure 100: CO_2 Sorbent Capacity of the "Large Scale" Materials as a function of number of cycles [S/C-3, GHSV-390 hr-1, TCout-600C, 1 atm]

ECM Series (Small and Large Scale Samples Extruded at CSMP)

In January 2005, CTV received samples (50 g each of material) die extruded at the new CSMP facility in Albuquerque, NM. The compositions had various concentrations of CaO and were either calcium or magnesium oxalates supported or in combination with alumina. The ECM Series Table containing the Sample ID, composition, and conditioning for each extrudate is located in Appendix F. Also included in Appendix F are the data tables and graphs of the average reaction efficiencies, gas composition, and CO_2 Sorption Capacity for each extrudate tested. The CO2 sorption capacity for all runs was adjusted for weight loss determined by CO2-TGA measurements. Weight loss or CaO determination was measured by CO2-TGA at CSMP facility and found comparable to a method using a muffle furnace at the CTV labs. The test method, data and results of the CaO Determination: Muffle Furnace vs. CO2-TGA can be found in Appendix G.

Small Scale

A summary of the test results from the micro-reactor runs for the small scale CSMP extrudates are shown in Figure 101 below. Consistent with CO2-TGA data, the material demonstrating the greatest stability throughout the test along with the highest CO2 sorption capacity is the CaO/Al2O3 (90:10) with 15% Al2O3 binder. A comparable CaO/Al2O3 (90:10) formulation with only 10% binder disintegrated during testing. Compositions containing higher concentrations of CaO disintegrated to powder by the end of the test (See Appendix H: Sieve Analysis). None of the CSMP extrudates were comparable to RTC benchmark extrudates.

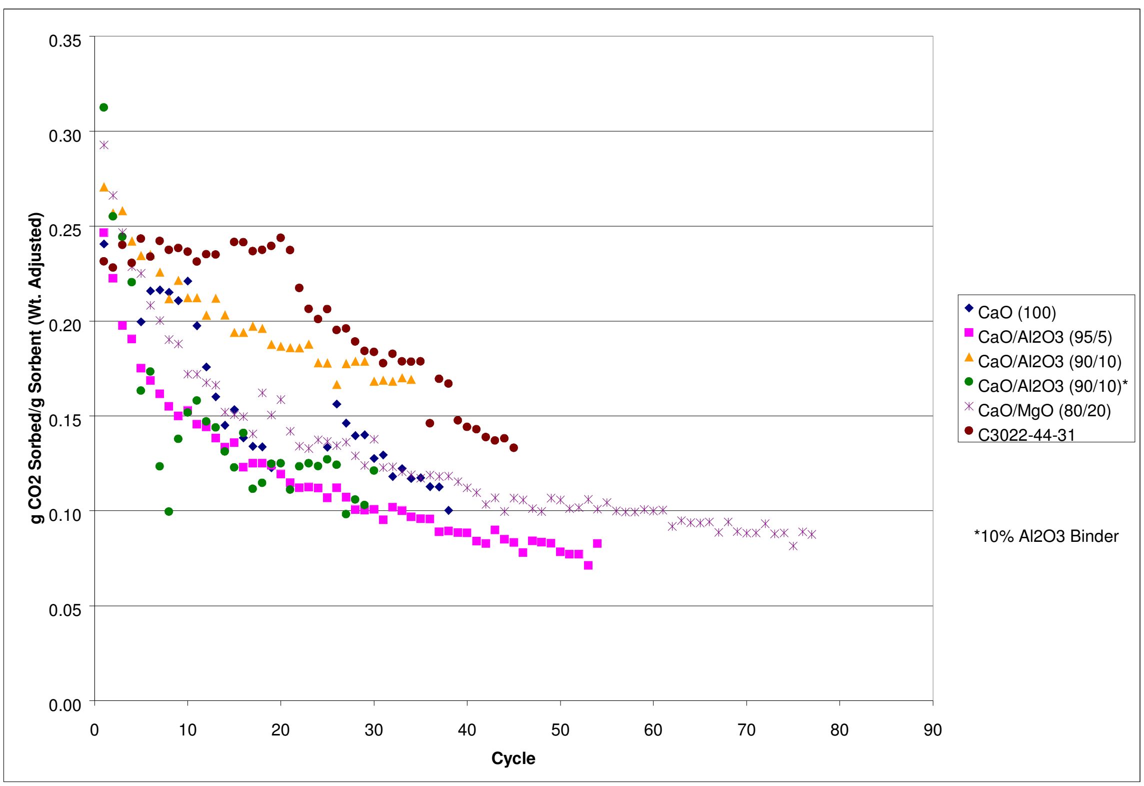


Figure 101: CO2 Sorbent Capacity of CSMP CaO/Al2O3 extrudates blends and RTC extrudate as a function of number of cycles [S/C-3, GHSV-390 hr-1, Tcout-600C, 1 atm]

Standard Material

Post run inspection of the CMSP material after the micro-reactor tests revealed noticeably thinner extrudates, approximately 24% weight loss, 15% fines denoting attrition of the extrudates. Efforts were made by CSMP to mitigate the reduction in cross section and improve extrudate integrity of the CaO/Al_2O_3 (90:10) with 15% Al_2O_3 binder. Also changes were made to the micro-reactor test procedure to reduce possible catalyst deactivation from contamination such as iron from corrosion of the reactor or silica from disintegration of the quartz wool. Inconel 800H replaced the 316 SS reactor. A study later by CSMP on "the Iron Poisoning Impact on Sorbent Performance" demonstrated little impact of iron poisoning on the CO_2 sorption capacity or adsorption kinetics. Fiberfrax replaced quartz wool at the inlet of the reactor. Another modification included reducing the temperature ramp rate from 19°C/minute to 5°C /minute for the first calcination. The lower ramp rate was used to reduce strain on the sorbent/catalyst bed.

CSMP submitted samples from the "standard" parent powder containing CaO/Al_2O_3 (90:10) with 15% Al_2O_3 binder dried/calcined at temperatures of 300C, 500C, 750C and 800C. Micro-reactor test results of the standard powder calcined at 300C, 500C and 800C are compared with other CaO/Al_2O_3 (90:10) with 15% Al_2O_3 binder materials and RTC extrudate in Figure 102 below. Results from ECM255061C750 micro-reactor tests were excluded from the data set due to problems with the reactor oven control. Limited sample quantities prevented multiple test runs of ECM255061C750.

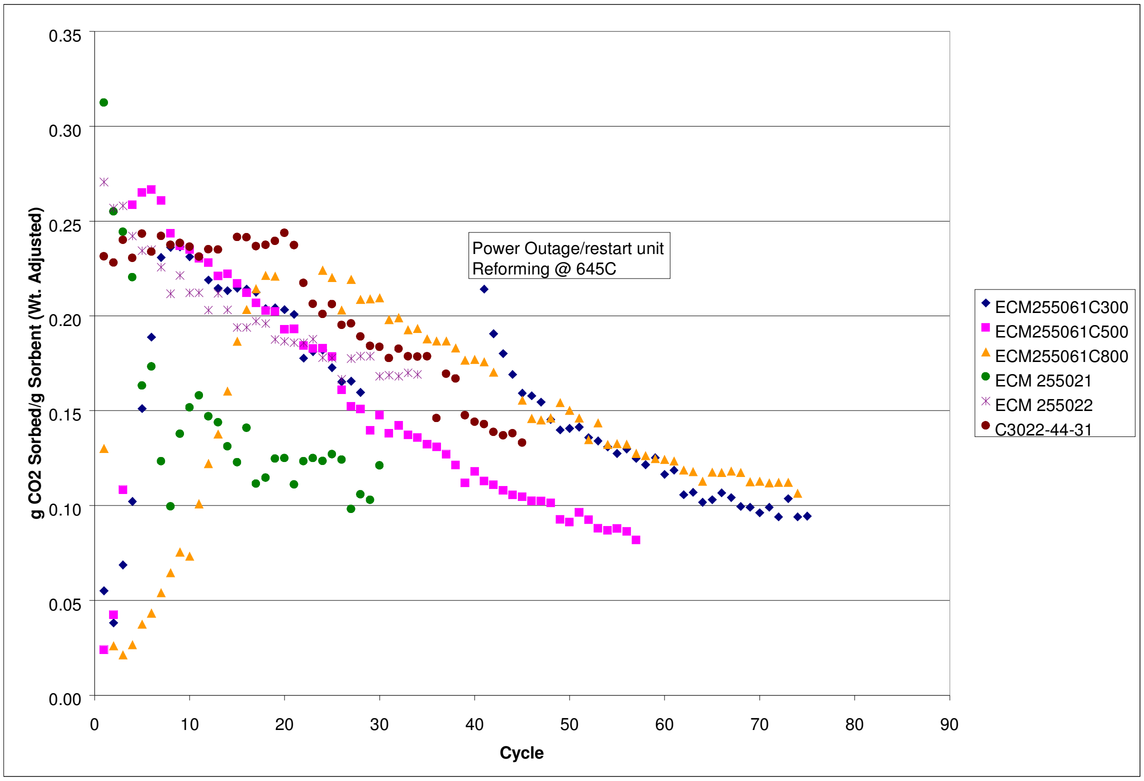


Figure 102: CO2 Sorbent Capacity of CaO/Al_2O_3 (90:10) with 15% Al_2O_3 binder materials calcined at different temperatures and RTC extudate as a function of number of cycles [S/C-3, GHSV-390 hr 1, TCout-600C, 1 atm]

Scale Up

Figure 103 compares the CSMP small scale preparations with die extrusion to larger scale production with screw extrusion. The performance of the screw extrusion products is comparable for CaO/Al_2O_3 (90:10) and improved for CaO/Al_2O_3 (95:5) demonstrating the process is scalable.

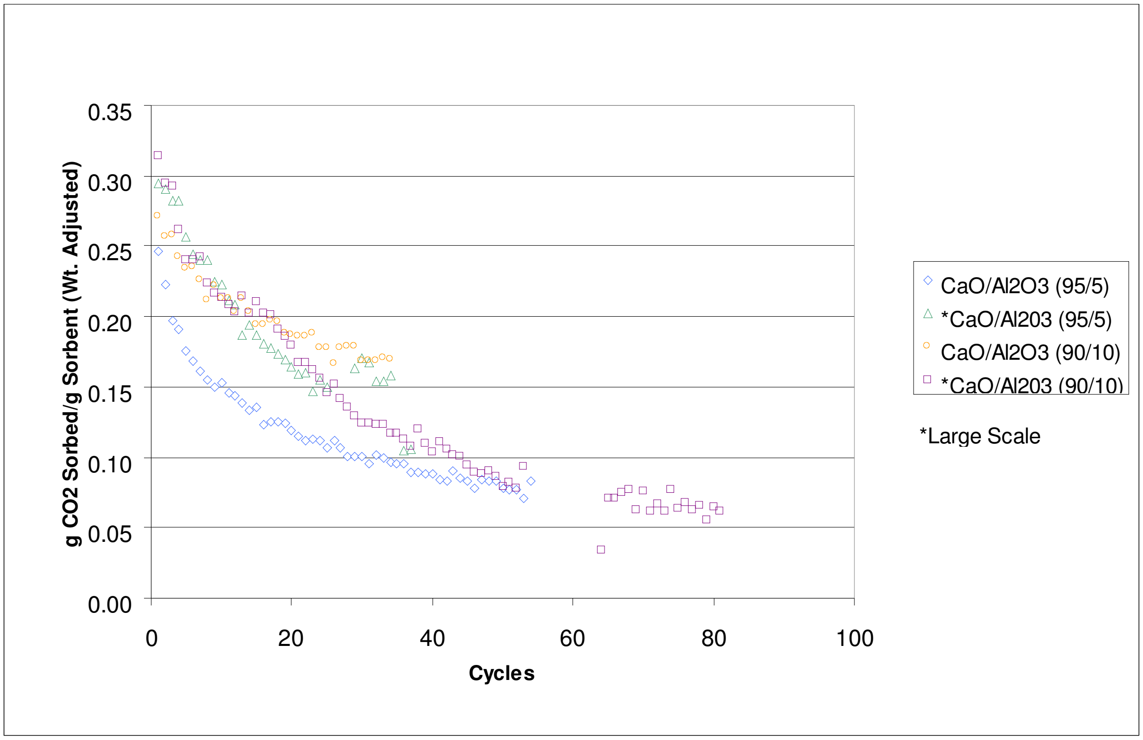


Figure 103: CO2 Sorbent Capactiy of CSMP "Small Scale" materials and "Large Scale" extrudates as a function of number of cycles [S/C-3, GHSV-390 hr-1, TCout-600C, 1 atm]

N2 Post Processing

In June of 2005, CSMP changed the post processing oven and atmosphere. The change in atmosphere from air to N2 was to maintain a safe environment and avoid high temperature excursions during post-processing. Materials ECM259011C and ECM259002C were submitted for evaluation. Both materials were CaO/Al_2O_3 (90:10) post-processed in the rotary calciner under nitrogen, but under different temperature, residence time and feed rates. Figure 104 compares the CO_2 sorption capacity for both materials with other CaO/Al_2O_3 (90:10) post-processed in the ITO oven under air. All materials compared were calcined in a Box Furnace in air at 750C. The materials post-processed under N2 demonstrate an increase in CO_2 sorption capacity than the materials post-processed under air. Post run sieve analysis for the materials post processed in N2 measured fines at 1.45% after 53 cycles and 1.51% after 77 cycles respectively. Extrudate integrity contributed to improved performance.

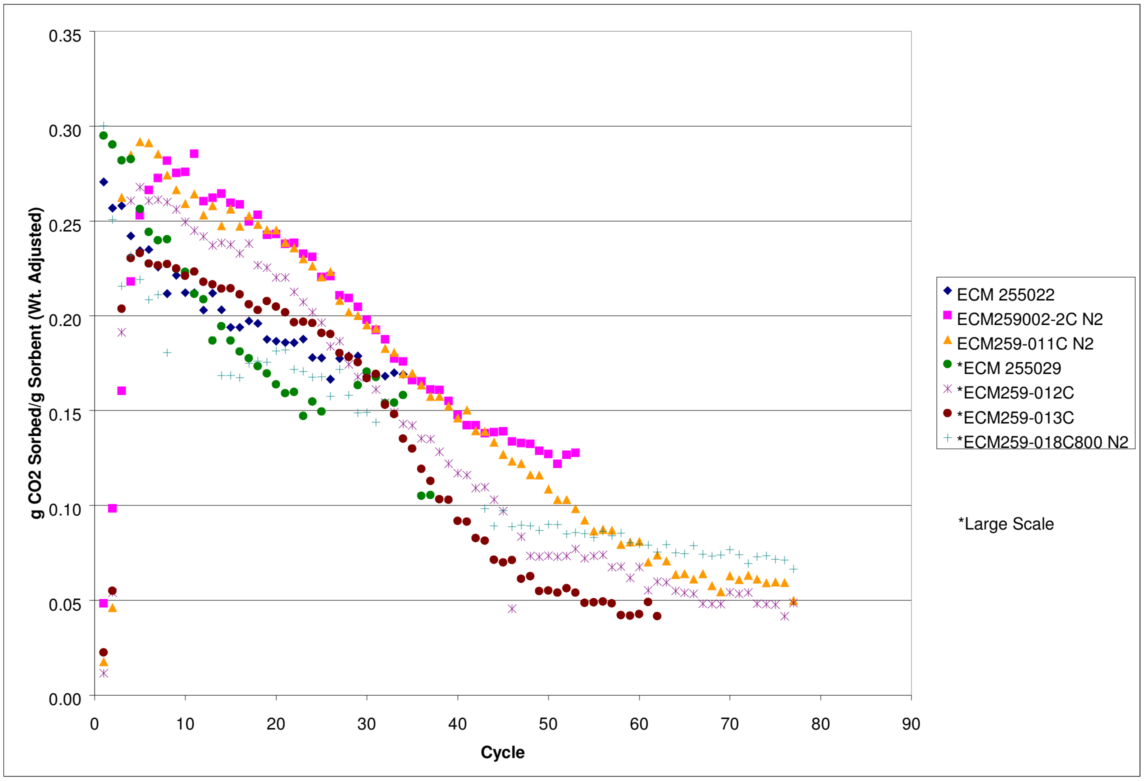


Figure 104: CO2 Sorbent Capacity of CSMP CaO/Al2O3 (90:10) with 15% Al2O3 binder materials post-processed under air and N2 as a function of number of cycles [S/C-3, GHSV-390 hr 1, TCout-600C, 1 atm]

Risk Review

Hazard and operability (HAZOP) analysis is a popular risk review technique to facilitate systematic searches for process hazards and potential operational difficulties. What-if scenarios were investigated to determine the effect on the catalyst activity. The scenarios include: 1) effect of multiple cycles on SMR activity 2) effect of multiple start ups due to unscheduled power outages, 3) effect of reduced S/C ratio due to water pump partial failure and complete failure and 4) sulfur slip through the guard bed.

Effect of cycles on SMR activity

The reduced of catalytic activity due to agglomeration of crystallites and loss of surface area is known as sintering. Commercial catalysts are designed for stable performance. Sintering under normal conditions proceeds slowly. However thermal cycling can impose strain on the catalyst support and promote sintering. SMR catalyst activity over multiple cycles was investigated to determine the effect on carbon conversion. Figure 105 shows the carbon conversion as a function time on stream for H_2 > 90%. The 10th minute for all cycles show near equilibrium carbon conversion for all cycles demonstrating SMR catalyst activity.

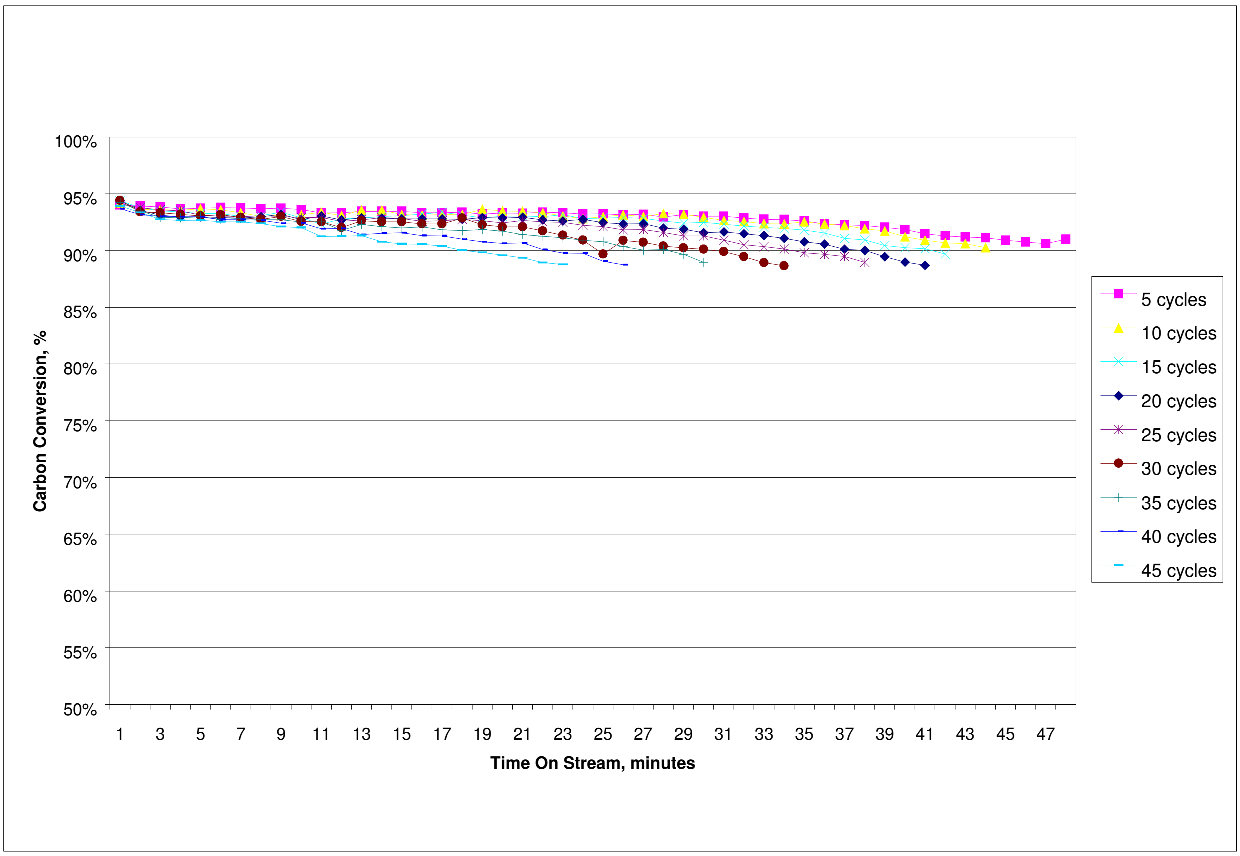


Figure 105: Carbon conversion as a function time on stream for H2 > 90% [S/C-3, GHSV-390 hr-1, TCout-600C, 1 atm]

CO_2 sorption studies in the literature indicate the CaO-CO_2 reaction initially proceeds by a rapid surface reaction-controlled step followed by a slower second stage product layer diffusion-controlled step CO_2 sorption. During the first 10 minutes, the CO_2 sorption on the surface occurs resulting in high methane conversion and higher H2 concentrations. The remaining time on stream the CO_2 sorption is controlled by diffusion. Sintering and loss of pore volume of the CaO sorbent material results in the loss of CO_2 sorption.

Multiple Starts

Multiple start ups could have a negative effect on equipment and catalyst bed alike. ECM25-9018C CaO/Al_2O_3 (90:10) post-processed in N2, was used for the first study. A 2 kg batch material, originally calcined at 750C, received additional post treatment to reduce weight loss. Significant weight loss can cause the sorbent bed to pack non-uniformly creating opportunities for gas channeling and reducing the residence time. Post treatment involves heating the sample to 800C to convert any CaCO3 in the material to CaO reducing the weight loss for the initial cycle. The amount of sample delivered was 1 kg due to problems with the initial extrusion and weight loss. There were two shut-downs: 1) unscheduled to do a lightning storm and 2) a mandatory shut-down in anticipation for Hurricane Rita. The unit remained off for 9 days. The multiple start / stops have a temporary beneficial effect as shown in Figure 106 similar to a steam soak.

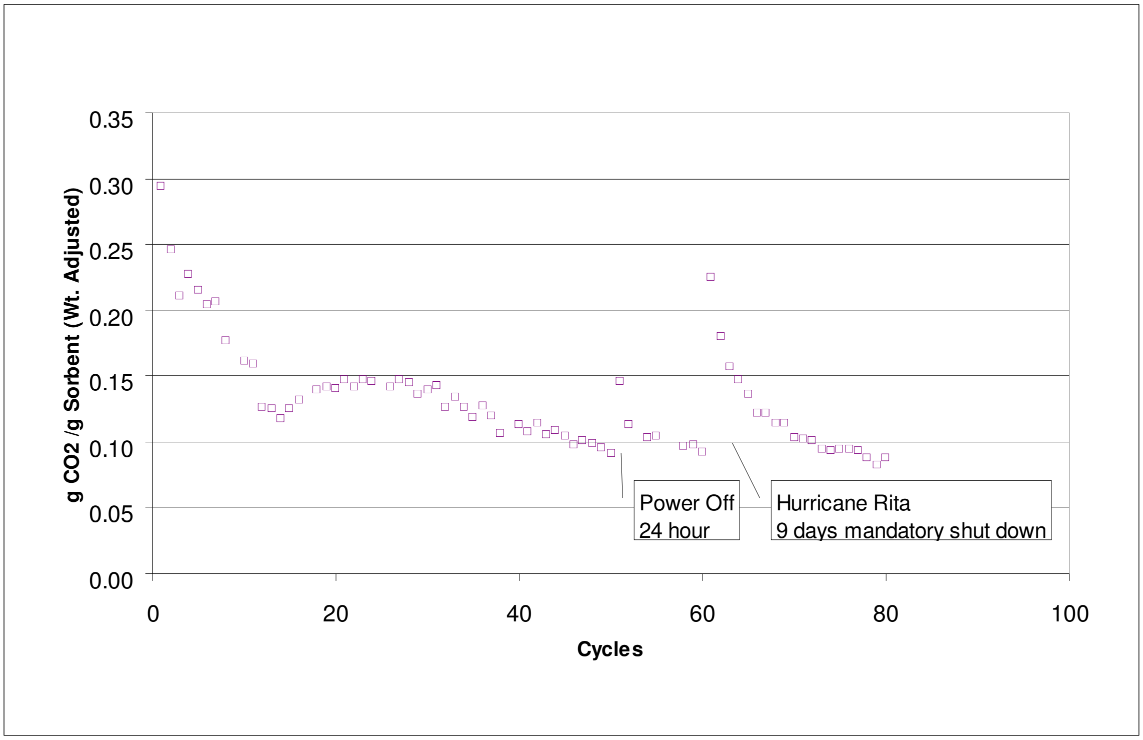


Figure 106: CO2 Sorbent Capacity of CaO/Al2O3 (90:10) with 15% Al2O3 after shutdowns as a function of number of cycles [S/C-3, GHSV-390 hr-1, TCout-600C, 1 atm]

Effect of S/C ratio on methane conversion and soot formation

S/C – 2.2

Early micro-reactor tests investigated lower steam to carbon ratios to improve system efficiency.

Pressure, atm	1	1
S/C	2.2	3.0
CH4 conversion-%	92	94
% Total Energy		
-Feed	73.3	71.0
-Fuel	26.7	29.0
@ Energy Efficiency to H2 (LHV)	78.7	77.9

Note: Controlled Oxidation Regeneration with 2 reactors in both cases.

In conventional steam methane reforming carried out at temperatures of 800ºC, S/C ratios of 3/1 or 4/1 are used to prevent soot formation and provide excess steam for the WGS reaction. Excess steam adds to the operating and capital costs. Operating at a lower steam to carbon ratio of 2.2 can produce as much as 92% H2 in reformate while improving operating and capital costs. Tests were performed to determine the effect of lower S/C ratio. Experimentally, a CH4 conversion baseline was established at 600ºC with the same CH4 flow rate as previous tests with S/C - 3/1. Next the temperature was increased in 20ºC increments to determine the CH4 conversion response. Each condition was maintained for three cycles. The system pressure was closely monitored. An increase in pressure drop across the catalyst bed would indicate carbon deposition on the catalyst. Figure 107 compares the average conversion efficiencies as a function of temperature for a CaO/MgO (80/20) material tested with a S/C 2.2 and 3.0.

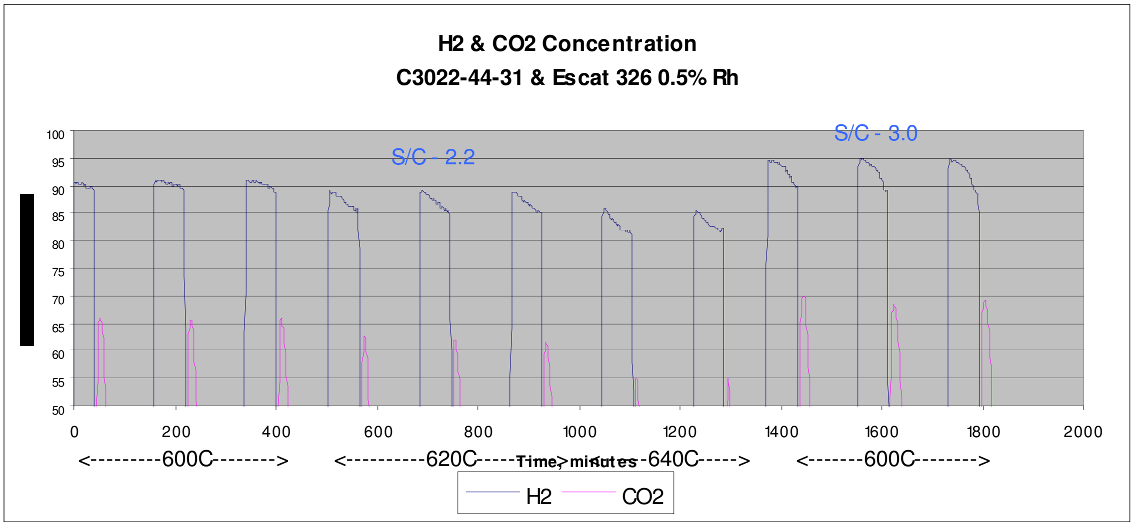


Figure 107: Average conversion efficiencies as a function of temperature for a CaO/MgO (80/20) material tested. S/C-2.2, GHSV-390 hr 1, TCout-600C, 1 atm]

No soot was detected at the lower S/C in a post-run inspection of the extrudates.

Water pump partial failure

Methane and other hydrocarbons found in natural gas will decompose into carbon and hydrogen in a steam reformer at elevated temperatures without water present. As reforming temperature increases so must the steam to carbon ratio to prevent soot formation. Two experiments were conducted: first with the water pump at half rate simulating a pump malfunction and second with no water flow simulating a complete pump failure. Each test was conducted with fresh catalyst.

In the first experiment, ECM255036 & Escat 326 were tested under normal conditions for the first 25 cycles. The water rate was reduced to half rate for 24 hours (8 cycles) resulting in a steam to carbon ratio of 1.5. Aspen equilibrium reaction calculations show a minimum S/C ratio of 1.6 at 600C (1 atm) to prevent carbon formation. At the end of 24 hour, the pump was returned to the full rate and the experiment continued until 92 cycles were complete. Figure 108 shows the CO2 sorption capacity for the 92 cycles when the pump was a full rate and H2 > 90%. Cycles with half the water flow rate are below 90%H2 and are not shown. A trend line through the data shows no permanent loss of sorption capacity due to a reduced water rate.

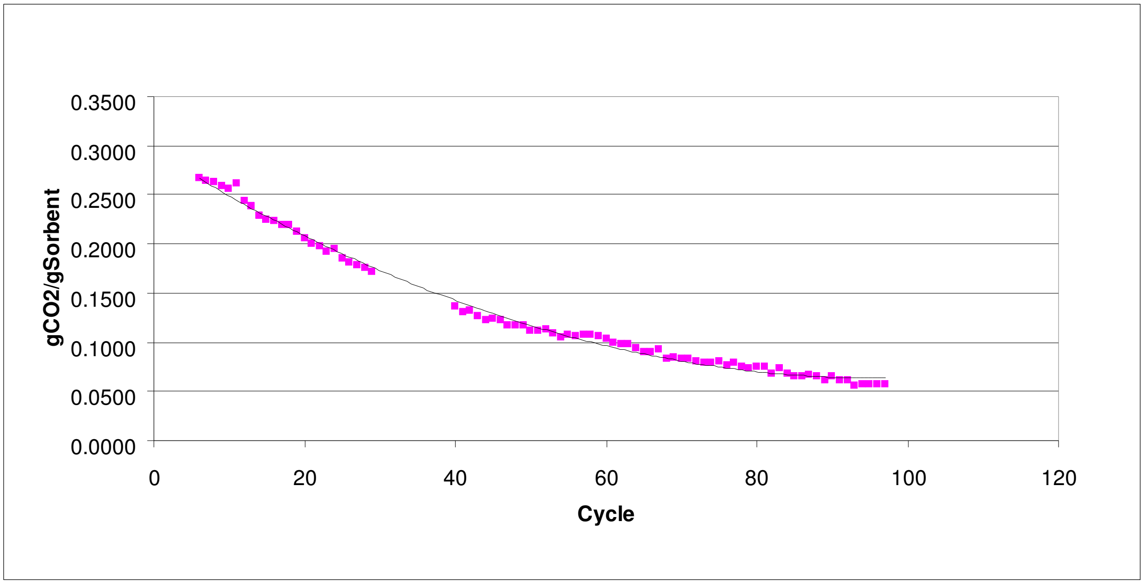


Figure 108: CO2 Sorbent Capactiy of ECM255036 as a function of number of cycles [S/C-3, GHSV-390 hr-1, TCout-600C, 1 atm]

In the second experiment, no water was allowed in the reactor for the first 10 cycles. Methane was delivered at the normal flow rate of 65 SCCM at 600C for 1 hour followed by a normal regeneration cycle. After 10 cycles, the water pump was started at the normal rate during the regeneration stage and remained on for the remainder of the test. Ten cycles translates to 30 hours without steam allowing time for soot to cover the catalyst and deposit in the pores. Figure 109 shows the gas compositions over time, the average gas compositions when H2 is greater than 90% and the CO2 sorption capacity as a function of the number of cycles. Figure 110 compares the CO2 sorption capacity of the material under normal SSR conditions and no water the first 24 hours followed by normal SSR conditions. The CO2 Sorption capacity shows no significant loss of sorption capacity due to a reduced water rate. Each graph shows the improvement in SSR performance and CO2 capacity with each successive cycle once the water is returned to the system.

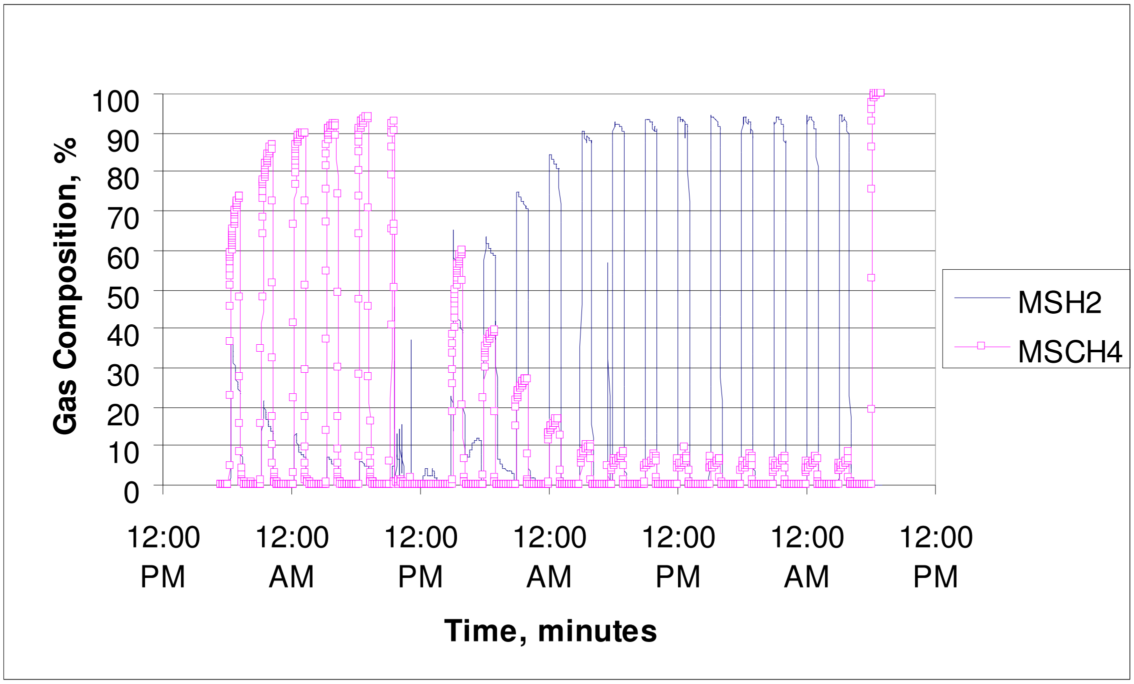


Figure 109: Effect of soot formation on H2 and CH4 concentrations plotted over time. [Cycles 1 - 6: S/C-0, GHSV-100 hr 1, TCout-600C, 1 atm]; [Remaining Cycles: S/C-3, GHSV-390 hr 1, TCout-600C, 1 atm]

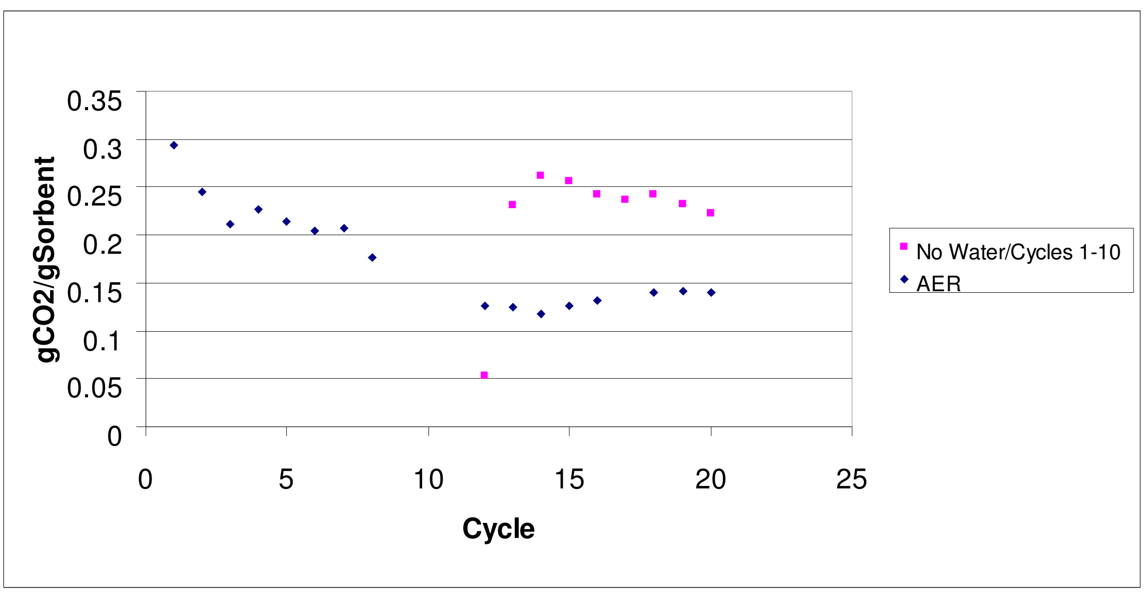


Figure 110: CO2 Sorbent Capacity of ECM259018C800 with and without steam as a function of number of cycles [S/C-3, GHSV-390 hr 1, TCout-600C, 1 atm]

Calcination Conditions

Previous studies show calcination below 750ºC is too slow to be of interest and temperatures above damage the materials due to sintering and loss of pore volume. However regeneration at the higher temperatures is more efficient as shown in Figure 111 and may have applications for powders rather than extrudates. However, regeneration temperatures exceeding 800ºC require expensive metallurgy resulting in higher capital costs.

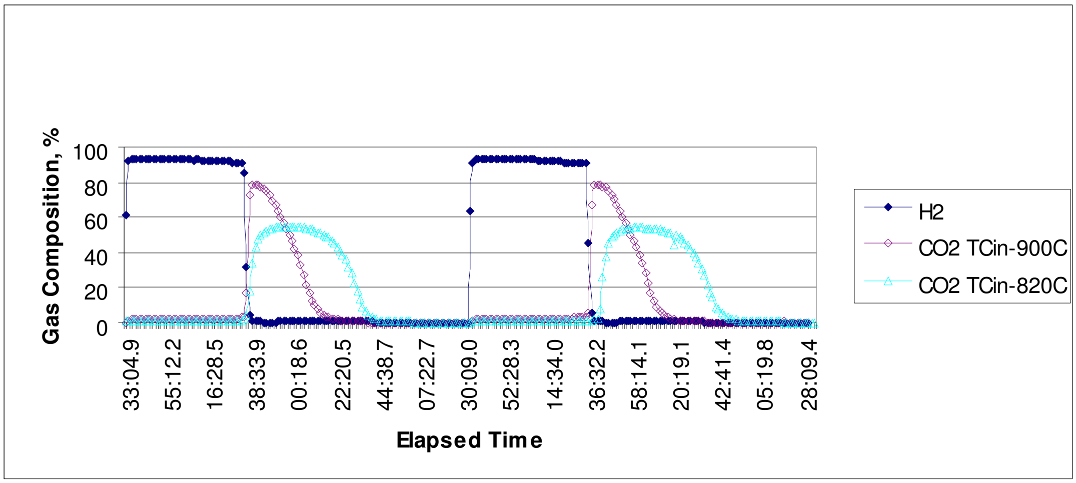


Figure 111: Effect of temperature on de-sorption rate of CO2 [S/C-3, GHSV-390 hr 1, TCout-600C, 1 atm]

Subtask 6.3: First Reactor Tests

The AutoSSR 1 kW reactor, located in Bay 54, was used to convert natural gas to H2 using a reformer that combined SMR, WGS and purification into one reactor. Simulation studies indicate the method of regeneration is the single most important factor in system efficiency. Different methods for regeneration can reduce system efficiency by more than 10%. Various regeneration control schemes listed below were tested.

- In-situ catalytic combustion gas regeneration
  a. Steam Methane Reforming (SMR) Catalyst
  b. Autothermal Reforming (ATR) Catalyst
  c. Combustion Partial Oxidation (CPO) Catalyst

- Metal Fiber Burner (MFB) combustion gas regeneration with Steam
- MFB combustion gas regeneration

Procedure

The reactor, described in subtask 5.3, was loaded with a mixture of steam reforming catalyst (*Engelhard*) and sorbent in a predetermined ratio. The aspect ratio of the packed bed was maintained greater than 4. Thermocouples to measure the vertical temperature profile were installed in the flange. The reactor was then flanged, leak tested and installed in the test bay.

As a first step, the sorbent was calcined by heating the bed to regeneration temperature using natural gas combustion exhaust from catalytic combustion. The calcination converts any carbonate to oxide form. Reactor exhaust gases were analyzed using a mass spectrometer. The concentration of CO_2 in the exhaust and/or the temperature profile in the reactor acts as a good indicator of extent of regeneration.

Followed by the regeneration step, the reactor was purged and cooled with steam and nitrogen. Nitrogen was used primarily to help with gas analysis. After purging, superheated natural gas and steam were introduced into the reactor. The hydrogen concentration was measured using the mass spectrometer. Declining H2 concentration with increasing methane and CO2 slip signaled the end of AER.

After the AER step, the reactor was purged with steam and nitrogen to remove any hydrogen from the system and cooled below the auto ignition temperature of natural gas. The natural gas, air and combustion heater were turned on to begin the ignition process.

In-situ Catalytic Combustion Gas Regeneration

Three different catalysts were tested as the regeneration combustor catalyst. All precious metal catalysts were provided by the Engelhard Corporation. The first generation process flow was from top down.

The first experiment used exclusively SMR catalyst mixed with the C3022-5-12. A pre-heated stream of natural gas and air were combined at sufficient temperatures to achieve light-off of the SMR catalyst. The catalyst mixed throughout the bed propagated the reaction through the reactor. Although light-off was achieved, the start-up time took several hours.

The top two inches of the SMR/C3022-5-12 mix was removed and replaced with ATR catalyst cut up into ¼” cubes. There wasn’t a significant improvement in the light off time due to bypassing of the catalyst. Finally, the ATR catalyst was replaced with CPO pellets. Five attempts to light off the catalyst proved unsuccessful. The natural gas line was checked for sulfur slip past the sulfur trap. Sulfur was detected. The sulfur trap was replaced with fresh sorbent and put back on line. The unit was purged with heated nitrogen overnight.

The unit was started the following morning. There was good contact with the gas stream and catalyst providing light-off. Thermocouples (TC) 10 - 14 monitored the process temperature with TC10 located at the inlet and TC 14 monitoring the exit of the reactor. The process ran continuously throughout the day producing two consecutive reforming cycles. The gas analysis and temperature data over the ten hour period is presented in Figure 112. The design flow rate used for the first cycle translates into 768 hr-1 gas hourly space velocity (GHSV). The flow rate was cut in half for the subsequent cycle due to the low natural gas conversion and low hydrogen yield in the first cycle. There wasn't any noticeable improvement in the second cycle. The low conversion was mainly due to the severe radial heat losses. The temperature differential from TC10 – TC14 was approximately 300° C.

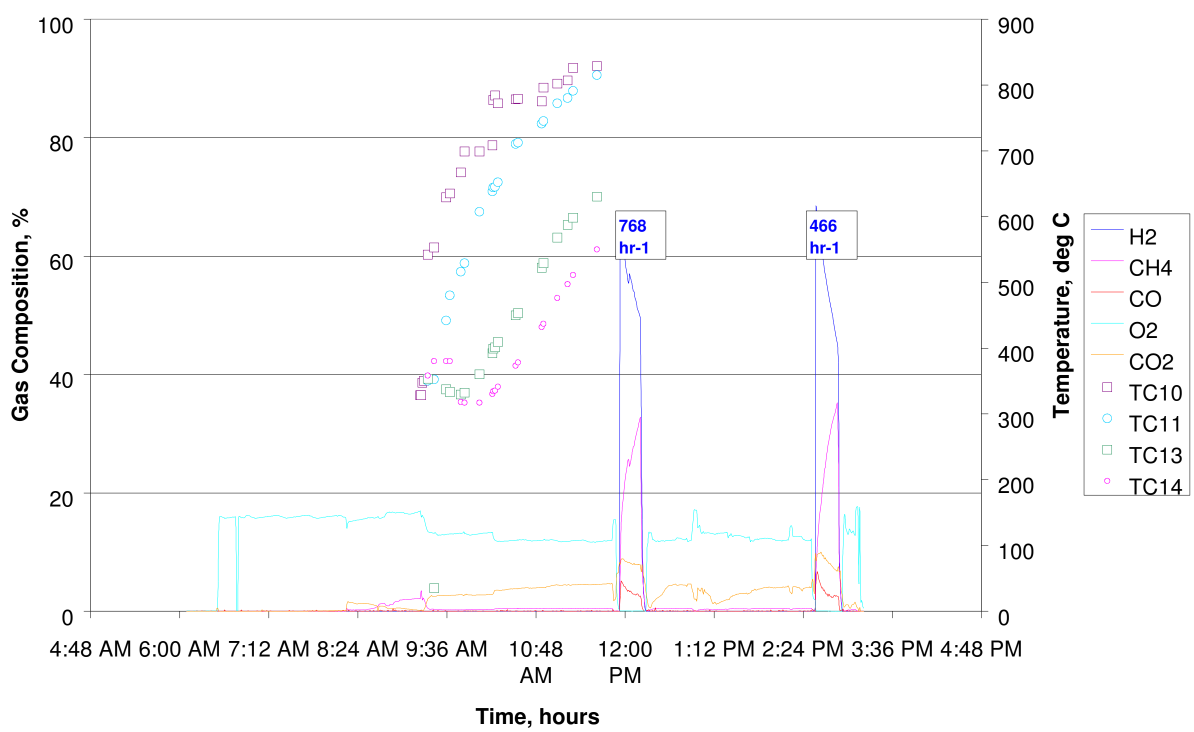
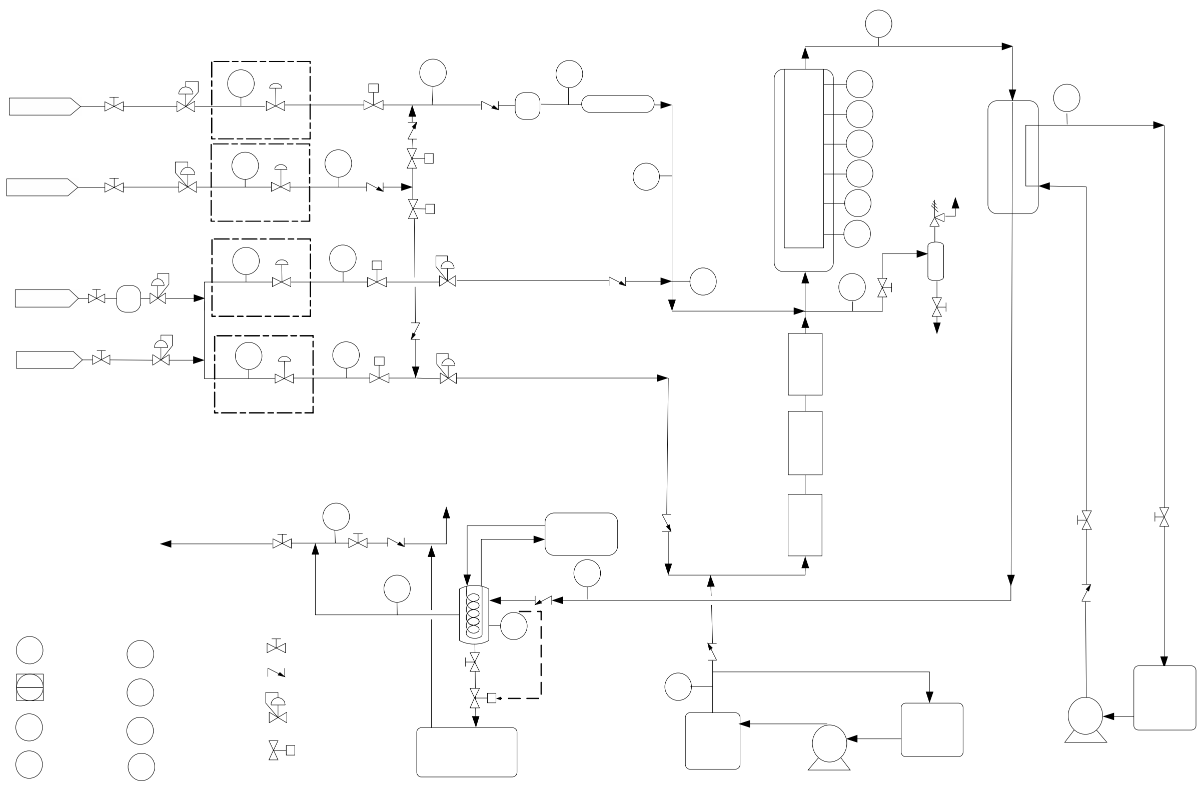


Figure 112: Gas analysis and temperature data plotted with respect to time. August 19, 2004

Several major modifications were made to mitigate heat losses. The process inlet and outlet lines were switched to allow the large flange (heat sink) to be on the downstream side of the reactor. The reversed process flow is shown in Schematic 4 below. The pre-heaters were aligned and installed directly below the inlet to the reactor to improve heat integration. Other minor modifications included changing water pump manufacturers to reduce water slugging, redesigning the manual user interface, and adding a Watchdog timer for unattended operations. Fresh CPO, SMR and C3022-30-32 catalyst was loaded into the reactor. Changes to the unit significantly reduced the start up time from 4 hours to 30 minutes without steam addition to transfer the heat. Although the start up time was reduced, the temperature profile across the bed indicated the need for additional insulation and heat trace.



Schematic 4: The reverse flow process AutoSSR 1 kW reactor in Bay 54

The reactor inlet was modified by the addition of a shower nozzle design as shown in Figure 113 below. The alumina based insulating sleeve was replaced with material having "R-factor" thirty times higher than the original alumina. A high temperature thermiculite flexitallic gasket replaced the existing gasket sealing the flange of the reactor. Additional heat trace was added. The downstream piping was modified to allow a greater flow rate of combustion gases.

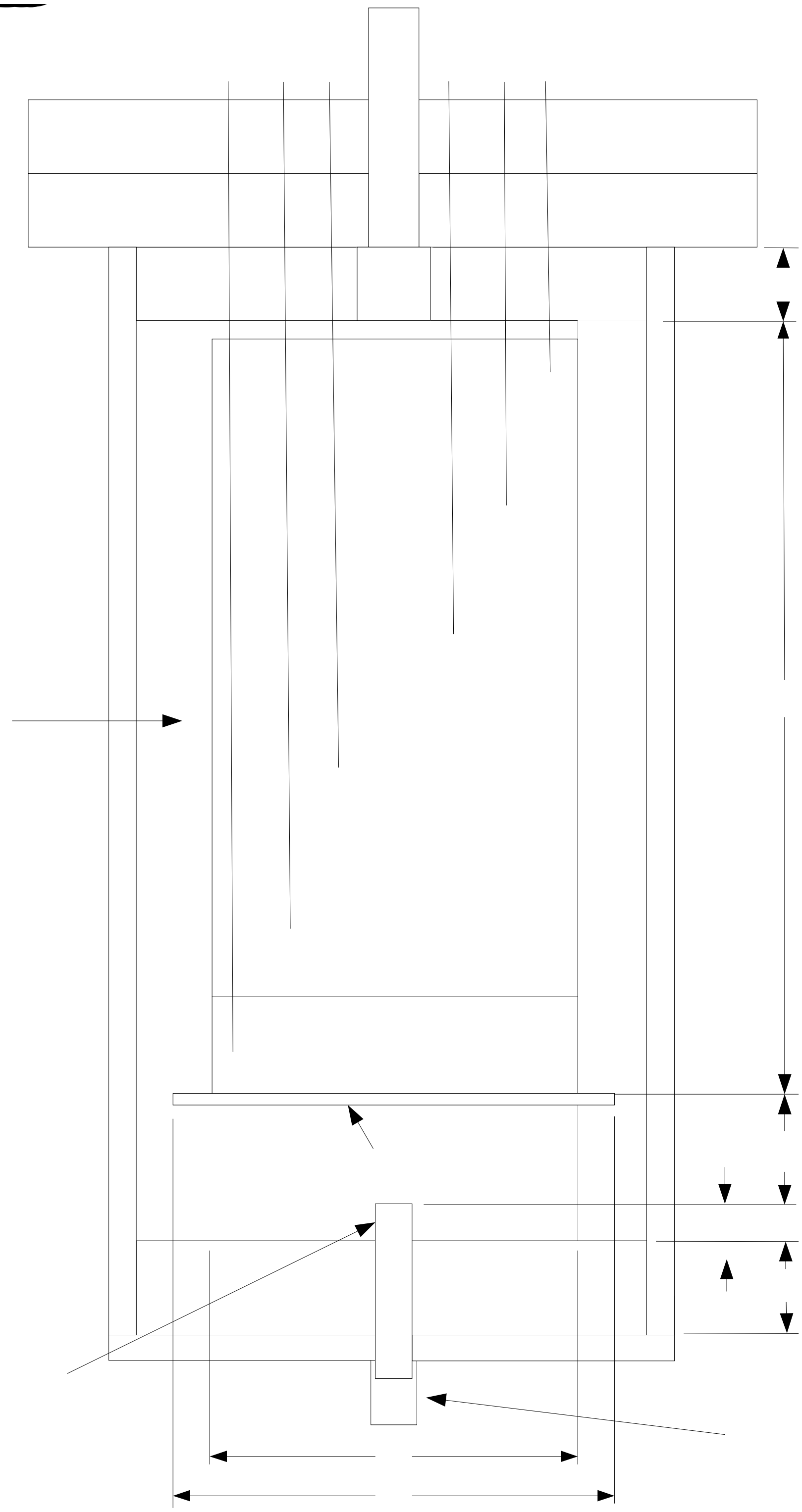


Figure 113: Schematic of In-situ Catalytic reactor design with nozzle

Tests following the modifications produced 90% H2 with consecutive start-up, reforming, and regeneration. The gas composition analysis and TCexit temperature are plotted with respect to time in Figure 114. Reforming cycles were short and hydrogen purity low due to a reforming steam temperature set-point of 500°C. Temperatures in the top section of the bed (sorbent only) weren't sufficient to regenerate the catalyst. However, the test run demonstrated that in-situ catalytic combustion of natural gas can generate enough heat to regenerate the catalyst/sorbent bed. In addition, the test run demonstrated rapid reliable light-off in steam, the ability of the control system to maintain a stable flame front and the ability to transition smoothly from reforming to combustion. A control script was developed toward total automation without manual intervention.

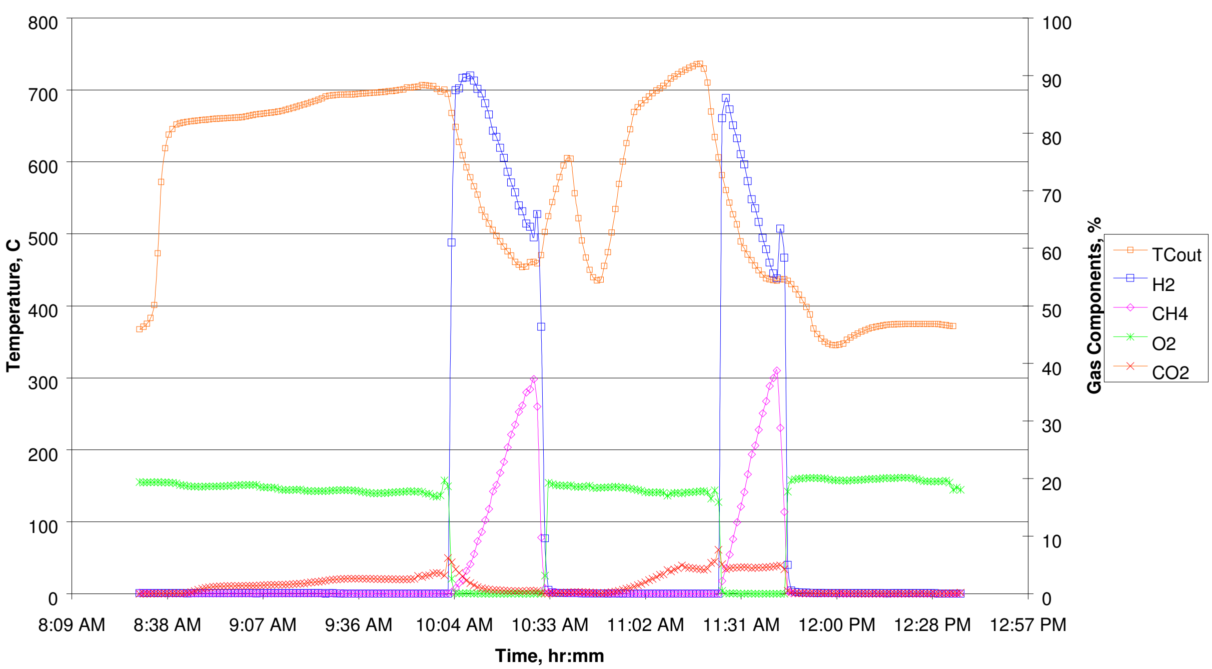


Figure 114: Gas analysis and TC exit temperature plotted with respect to time. 11/11/04

Tests continued to improve the control strategy to prevent high temperature excursions that can occur with endothermic CO2 evolution. Additional reactor modifications were considered to reduce the T of 200°C from TC8 (preheater exit) to TC6 (reactor inlet) and balance the electrical load on the system. Figure 115 and 116 below show the gas compositional analysis and reaction efficiency from a single cycle from a test run on 12/14/04. Light off occurred at 330ºC and methane slip throughout the regeneration cycle remained below 1.6% indicating good combustion catalyst activity. Hydrogen concentration during the reforming reached >90% and remained above 80% for 48 minutes. Based on the reaction efficiency profile of the reforming

cycle, the endothermic reaction, radial heat losses, and 600ºC steam reduced the CH4 conversion efficiency while improving water-gas shift efficiency and CO2 fixing. A higher inlet steam temperature was required. An Aerorod heater was ordered from Zeton to install directly into the reactor to deliver steam and natural gas at the catalyst interface. In the interim, a 316ss coil replaced the straight reforming gas delivery line to eliminate water slugging and raise the temperature of the steam.

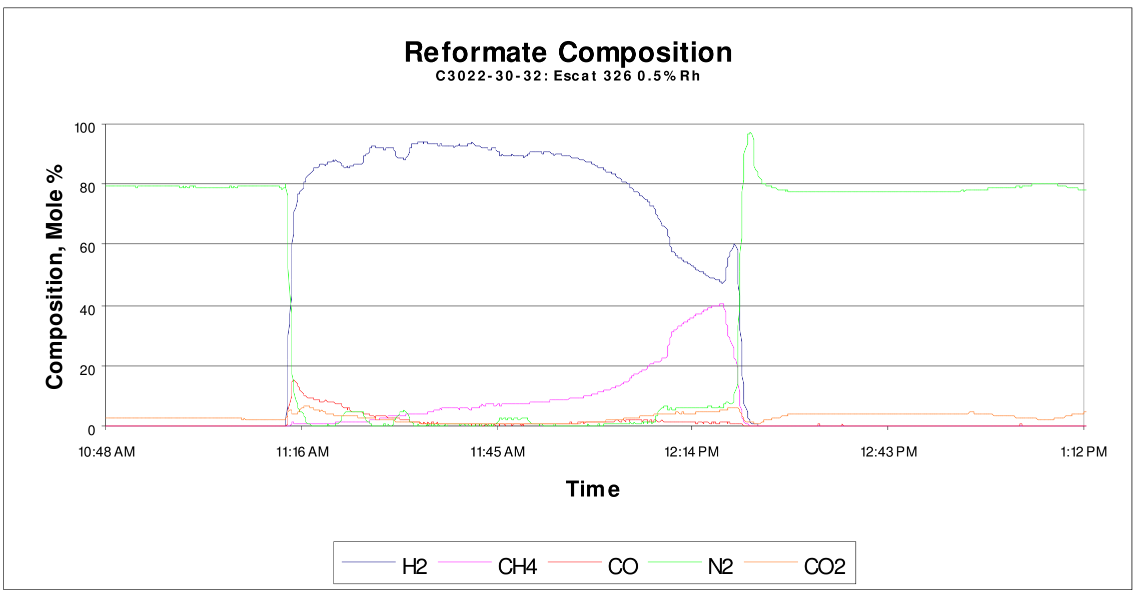


Figure 115: A typical concentration profile during a reforming cycle. 11/11/04

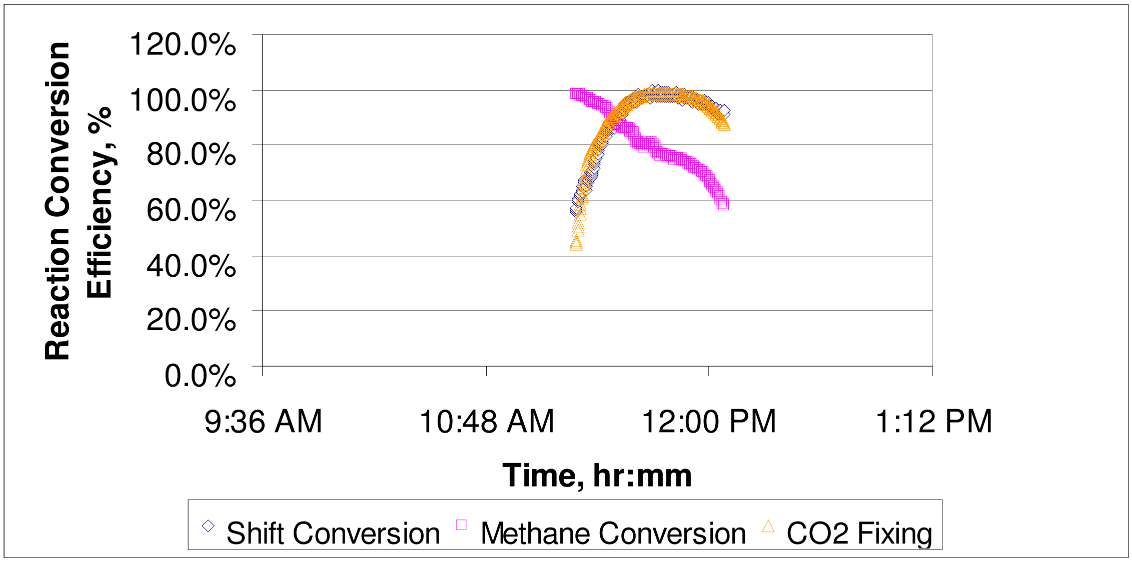


Figure 116: Reaction Efficiency: H2 > 80% plotted with respect to time

A 24 hour automated test was completed without operator interference with the new steam coil. The regeneration cycle was followed by a 46 second steam purge. Reforming immediately followed the steam purge with a S/C ratio of 3.5, reactor inlet temperature of 626°C and GHSV of 896 hr-1. The gas compositional analysis plotted over a 24 hour test period is in Figure 117 below. Low hydrogen purity was the result of low CO2 sorption in a hot reactor bed. The purge cycle wasn't long enough to allow the bed to cool to the optimum CO2 sorption temperature for AER.

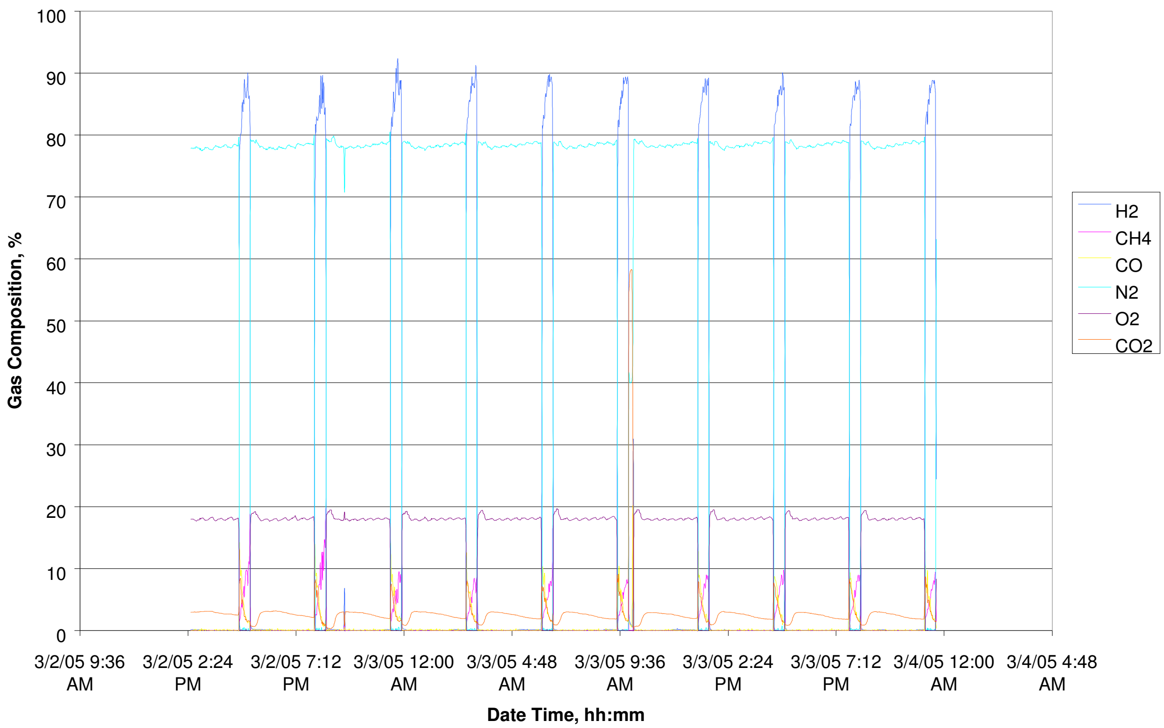
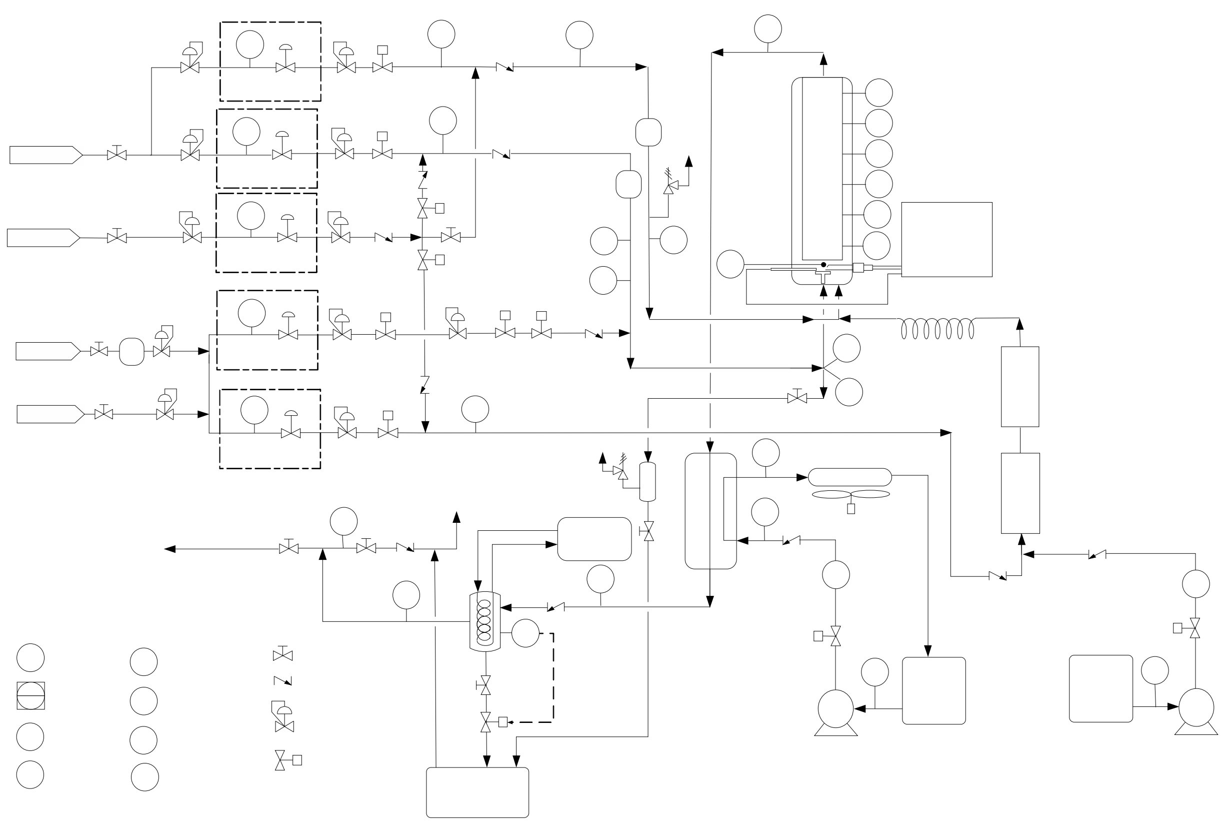


Figure 117: Gas Compositional analysis plotted over a 24 hour automated test

The in-situ catalytic combustion design was used to test operating parameters such as S/C ratios and temperature distribution in addition to sorbent durability. Hydrogen purity reached 94% but additional operational changes including the use of best available sorbent still to be implemented. Tests of the first 1kw reactor revealed that the heat transfer rates using an electrical heater and catalytic combustion during calcination was too slow to achieve reasonable throughput. As a result the reactor was modified to use natural gas combustion as the method for heating the sorbent bed and driving off CO2. It is expected that these changes would improve hydrogen purity to the levels seen in the micro-reactor testing.

Metal Fiber Burner (MFB) combustion gas regeneration with Steam

The AutoSSR 1 kW Unit in Bay 54 was modified and fitted with a Metal Fiber Burner (MFB) for gas regeneration described in ***Subtask 5.4: Second 1 kW Reactor Design***. The reactor schematics were identical except the reactor in Bay 54 is 5” shorter with a 11” catalyst bed. The process was similar except the Aerorod heater replaced the wick boiler as the steam super-heater. Zeton designed built the Aerorod coil to provide steam delivery directly into the catalyst bed. In addition, the unit was de-bottlenecked to allow for higher combustion gas flow. A MOC was completed. Reactor internal modifications were made including the addition of a secondary air line. The Aerorod steam coil installed and additional control programming completed to control the heater temperature. During the reactor modifications, work on the control strategy led to total automation via the executable code in the Fieldpoint Realtime® modules. The same basic procedure described in ***Subtask 5.4: Second 1 kW Reactor Design*** was also used.



Schematic 5: AutoSSR 1 kW reactor with MFB in Bay 54

Results

ECM259012 sorbent material and Engelhard Escat 326 were loaded in the AutoSSR 1 kW reactor fitted with a MFB in Bay 54. CSMP delivered 1.7 kg of this "standard" material calcined in a box furnace at 750ºC with a reported CO2TGA %Wt. Loss of 21% (See Appendix A). Figures 118, 119, and 120 show Average Reaction Efficiencies (H2>90%), the Average Gas Composition, and the CO2 absorption capacity compared to micro-reactor (Weight Adjusted) of the material with cycles.

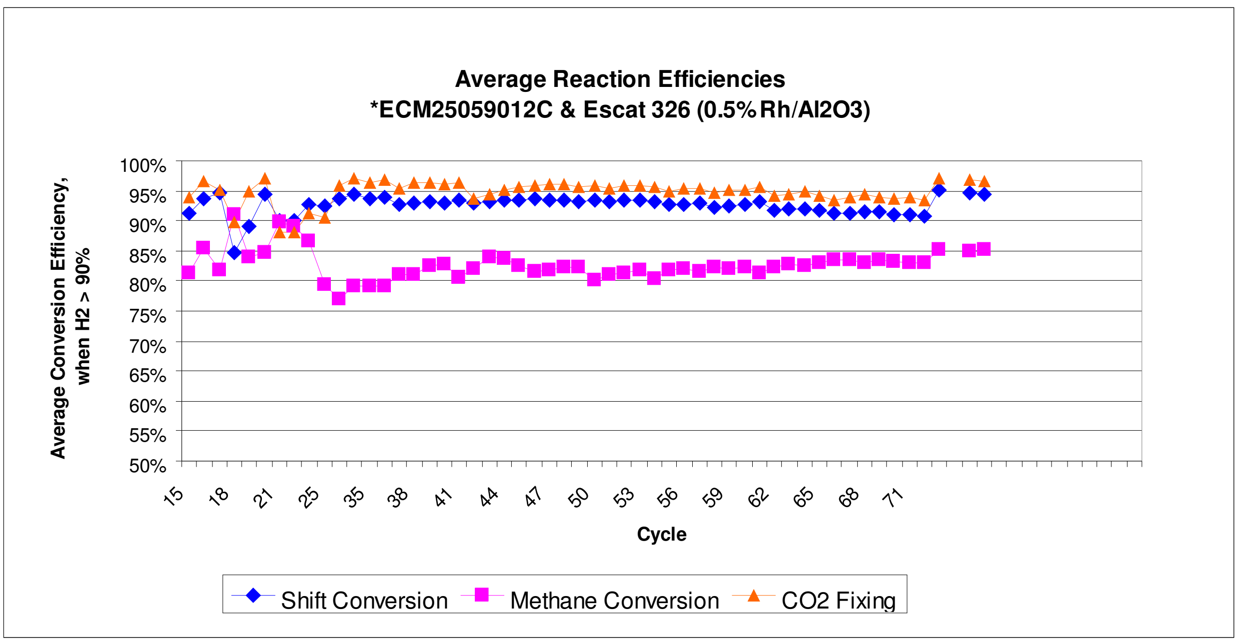


Figure 118: Average Reaction Efficiencies of ECM259012

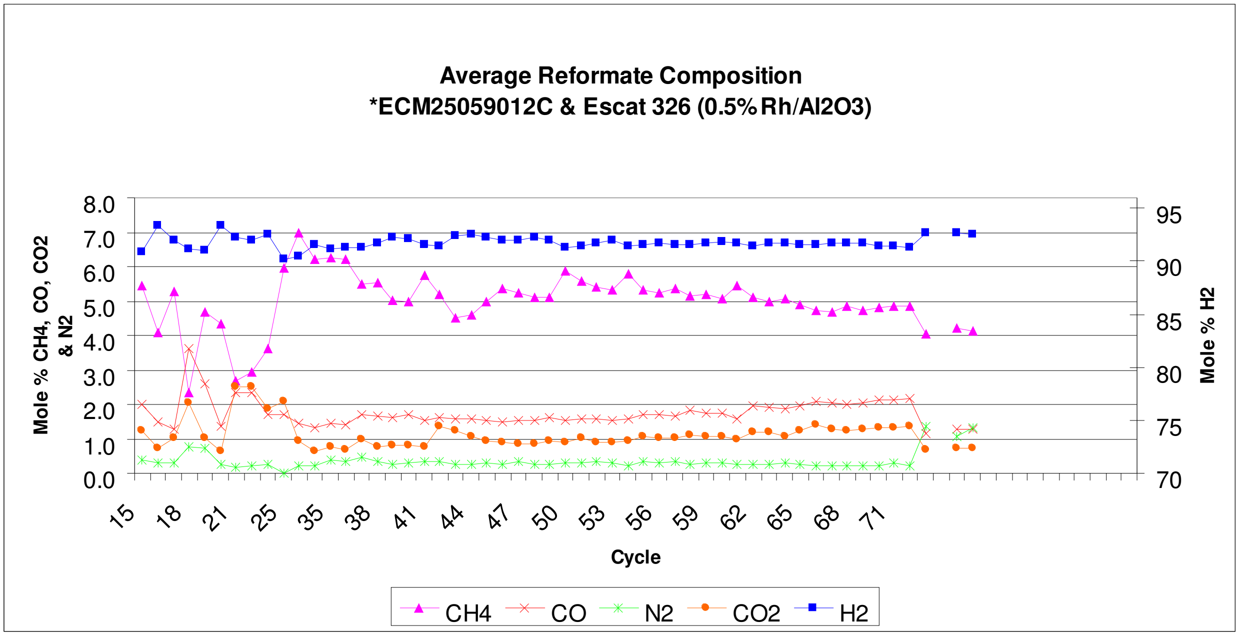


Figure 119: Average Reformate Composition of ECM259012 when H2 > 90%

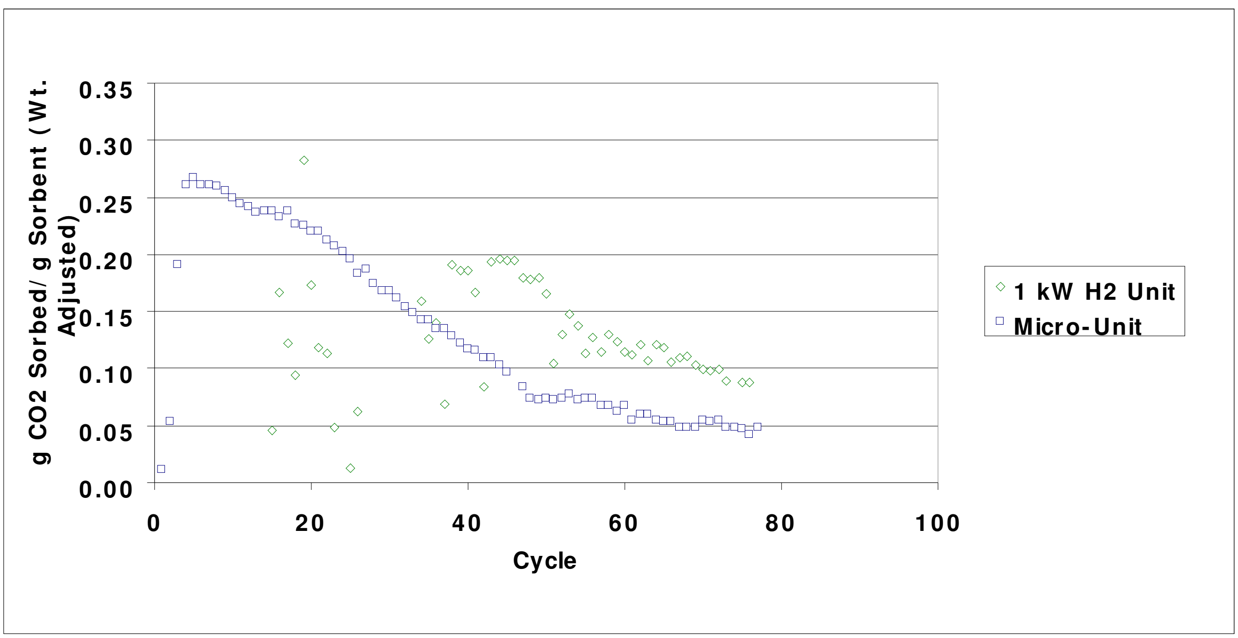


Figure 120: CO2 absorption capacity of ECM259012 when H2 > 90%

The first 35 cycles were optimization cycles. The optimum feed temperature to obtain sustainable high H2 concentration depends on the heat balance. The reaction temperature tends to decrease due to the heat imbalances of the endothermic steam reforming (H =-206kJ/mol) and exothermic CO2 sorption (H =178kJ/mol), feed temperatures, initial bed temperature, shift conversion, and heat losses in the adiabatic reactor. After 35 cycles, small incremental improvements were made during each cycle to maximum H2 production. The Average Reaction Efficiencies were determined for when H2>90%. As evident from the figure, optimization of the process continuously improved with time. The cooler bed temperatures favor higher CO2 Fixing Efficiencies and Water Gas Shift efficiencies, but lowered CH4 conversion. The H2 concentration (H2>90%) averaged around 92 – 93% for each cycle. As the bed and steam temperatures were optimized, the average methane slip decreased with each cycle.

The lower capacity or missing data points in the graph were due to either upset conditions in the inlet feed or loss of flow to the gas analysis equipment. CO2 sorption the capacity of this material decreased with cycles. The AutoSSR 1 kW unit had significantly higher CO2 sorption capacity when compared to the micro-reactor tests. Earlier studies report the decline in CO2 sorption capacity is due to calcination and sintering. Earlier cycles on the AutoSSR 1 kW were incomplete 1 hour cycles and a reduced regeneration cycles reducing time at high temperature. Thus the decline in CO2 sorption capacity is less.

Subtask 6.4: Second Test Stand Modification and HAZOP

Second test stand was built based on first test stand design with modifications to incorporate metal fiber burner and a wick boiler. The modifications were then reviewed using a Management of Change (MOC) procedure.

Subtask 6.5: Second Reactor Tests

Second reactor was used to test absorption enhanced reforming with combustion gas regeneration. Three different materials were tested in Bay 68.

Procedure

The reactor, described in subtask 5.4, was loaded with a mixture of steam reforming catalyst (*Engelhard*) and sorbent in a predetermined ratio. The aspect ratio of the packed bed was maintained greater than 4. Thermocouples to measure the vertical temperature profile were installed in the flange. The reactor was then flanged, leak tested and installed in the test bay.

As a first step, the sorbent was calcined by heating the bed to regeneration temperature using natural gas combustion exhaust from the metal fiber burner (MFB). The calcination converts any carbonate to oxide form. Reactor exhaust gases were analyzed using a mass spectrometer. The concentration of CO_2 in the exhaust and/or the temperature profile in the reactor acts as a good indicator of extent of regeneration.

Followed by the regeneration step, the reactor was purged and cooled with steam and nitrogen. Nitrogen was used primarily to help with gas analysis. After purging, superheated natural gas and steam were introduced into the reactor. For our later test runs, the purging was continued till the reactor temperature profile reached reforming conditions. The hydrogen concentration was measured using the mass spectrometer and H2Scan®. The end of absorption enhanced reforming was characterized by declining hydrogen concentration. For our first two test runs, we employed shorter reforming-regeneration cycles to study the effect of cycling on CO_2 absorption capacity. However we realized that this testing protocol might introduce artifact in the capacity data, especially in the earlier cycles. So for the last test run, the reforming step was carried out for 1 hour. Longer reforming step also results in longer regeneration step.

After the reforming step, the reactor was purged with steam and nitrogen to remove any hydrogen from the system. Once purged, air was introduced into the burner to cool the burner housing. After the burner housing is cooled below the auto ignition temperature of natural gas, burner control module is turned on to begin the ignition process.

All aspects of the above procedure was automated and controlled via the executable code in the Fieldpoint Realtime® modules. The control code was also programmed with safety sets that trigger shutdown of the unit in case of any parameter exceeding the safety limit. The safety sets were programmed such that they were active either during a specific step or remain active over any automated operation.

Figure 121 shows a typical concentration profile during a reforming cycle.

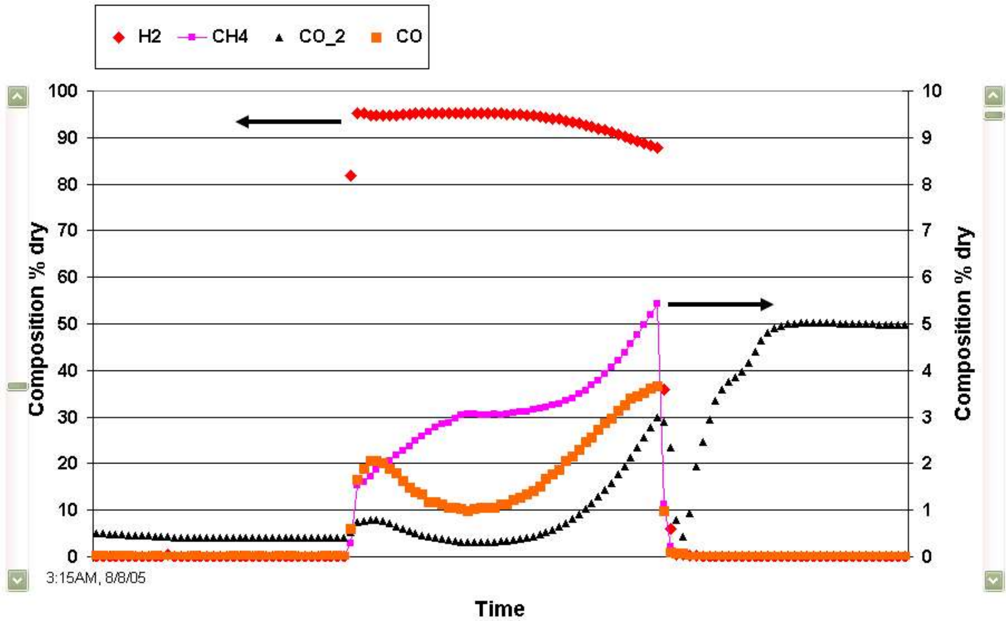


Figure 121: Typical concentration profile during refoming step

Three materials were tested in the second 1 kW reactor design. The CO_2 absorption capacity reported in measured based on a reforming step producing hydrogen concentration of more than 90%.

Results

C4032-42-44

This material was made in small quantities in a process designed for small batch production. Figure 122 shows the CO_2 absorption capacity of the material with cycles.

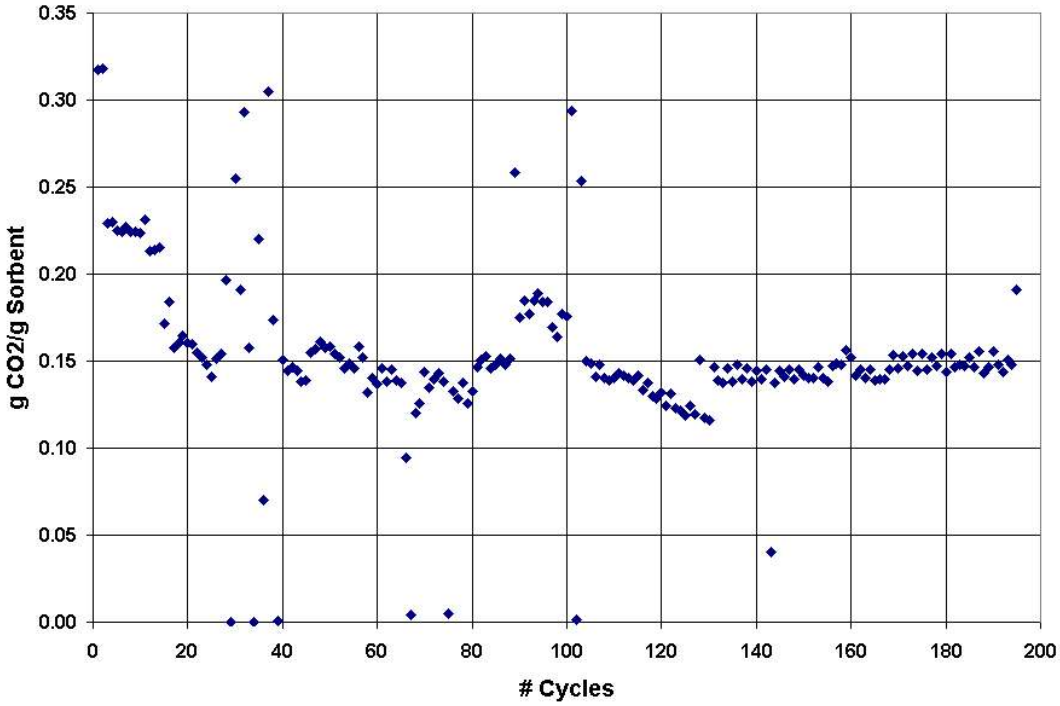


Figure 122: CO2 absorption capacity of C3022-42-31

As evident from the figure, the capacity of this material is decreased with cycles and reached a plateau after 60 cycles. The deviations in data showing higher capacity compared to the general trend were due to longer regeneration period. The lower capacity data points in the graph were due to either upset conditions in the inlet feed or loss of flow to the gas analysis equipment.

ECM25-5036

This sorbent material is produced in a process designed for large scale production. Figure 123 shows the CO_2 absorption capacity of the material between cycles 1-200. As seen from the figure, the performance of the material was not good up to 170 cycles. Upon inspection, we found out water condensation on the sorbent near exit of the reactor. On further investigation, this condensation was attributed to an unplanned shutdown during reforming step. This caused steam condensation near the exit of the reactor. So, we modified our setup to provide a nitrogen purge in case of an emergency shutdown to prevent this occurrence.

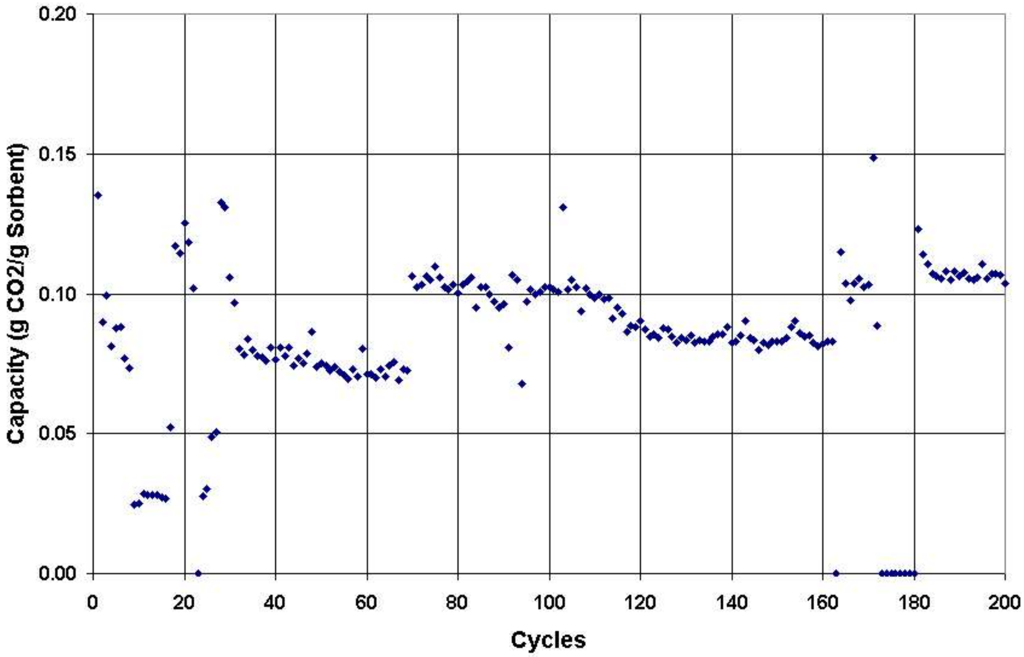


Figure 123: CO2 absorption capacity ECM25-5036 1-200 cycles

We replaced the sorbent and steam reforming catalyst from end of the reactor with fresh sorbent and catalyst. Figure 124 shows the CO_2 absorption capacity of the reactor after 200 cycles.

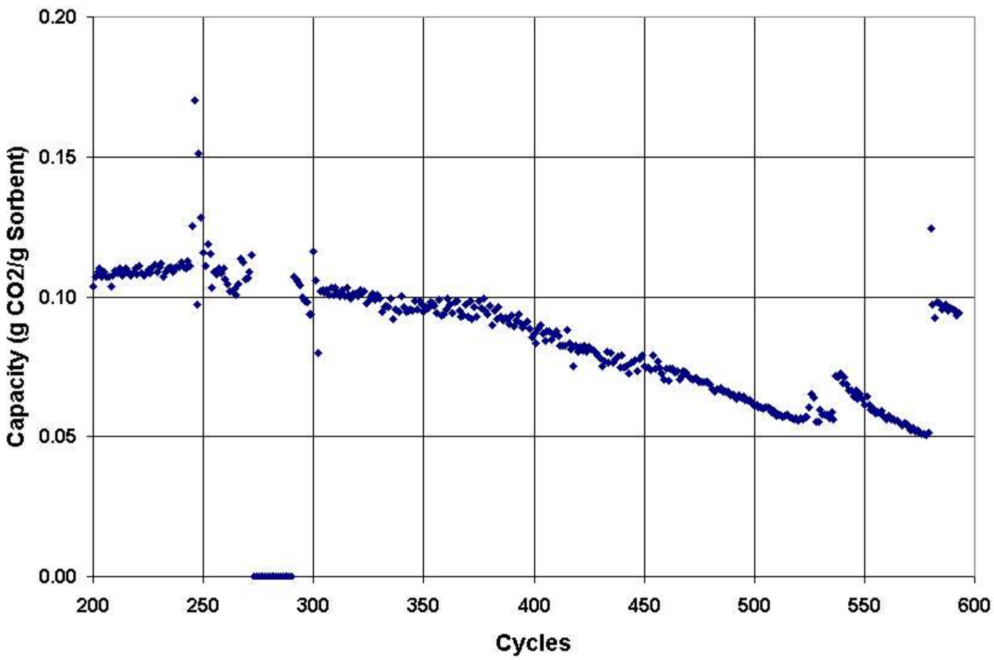


Figure 124: CO2 absorption capacity of ECM25-5036 > 200 cycles

The performance of the reactor improved significantly after 170 cycles but showed steady decline. The absence of data between cycles 270 and 283 was due to unplanned shutdown of the mass spectrometer.

After 580 cycles, the material was subject to steam soak process in which the material was exposed to steam at about 300-400 C for about 12 h. This process improved the performance of the material significantly from 5% to 10% capacity. But, the steam soak could not retain this improved performance. Further studies with steam soak were done with our third candidate material.

ECM25-9013C

This sorbent material was also produced using large scale production method. The CO_2 absorption capacity of the material is presented in Figure 125.

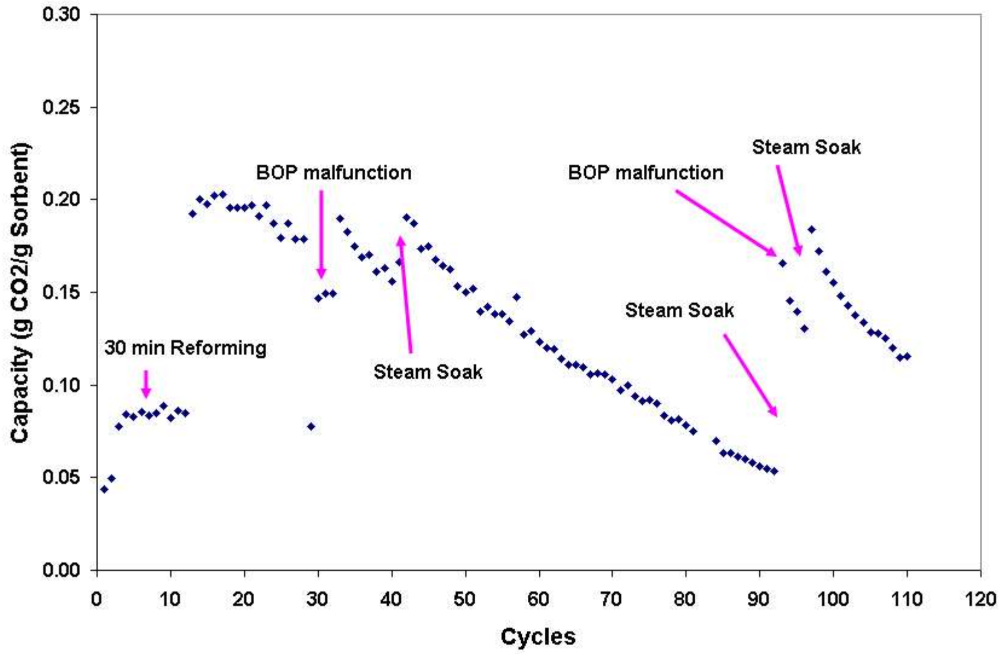


Figure 125: CO2 absorption capacity for ECM25-9013C

The lower capacity in the first 12 cycles is an artifact of shorter reforming time. The CO2 capacity is higher with 1 hour reforming step, the design point for the reactor. As evident from the figure, the capacity of the material declined steadily with cycles barring the unplanned shutdown due to balance of plant components. As mentioned in the testing procedure, the cycle time for this material was 6 hours including the inter-step cooling as compared to cycle time of 1.5 hours for ECM25-5036. Hence, the rate of decline of this material seems more rapid than

ECM25-5036. But this is in accordance with the theory that the rate of decline in capacity is proportional to the amount of time the sorbent is exposed to high temperature.

During the course of the testing, we tested the effect of steam soak in recuperating the sorbent capacity. As evident from the data, the steam soak does improve the performance significantly but the following decline in capacity is more rapid.

Conclusion

The CO_2 absorption capacity of the material made using large scale production method did not meet the necessary capacity targets. In small scale production method, the capacity was stable at 15% but still lower than the original target of 30%.

Subtask 6.6: Third Test Stand Modification and HAZOP

The third test stand was not constructed as we decided not to pursue the 5 kW reactor design and testing.

Subtask 6.7 Third Reactor Tests

The third test stand was not constructed as we decided not to pursue the 5 kW reactor design and testing.

Task 7: 50kW Fuel Processor Construction

Since we did not meet the Go/No-Go criteria in terms of expected thermal efficiency, it was decided not to pursue this task.

Task 7: 50kW Fuel Processor Construction

After the conversation with DOE program manager, it was decided that 50 kW fuel processor will not be constructed.

Task 8: 50 kW Fuel Processor Testing

No work was done under this task due to decision on Task 7.

Task Schedule

Task Number	Project Milestones	Task Completion Date				Progress Notes
		Original Plan	Revised Planned	Actual	Percent Complete	
1	Reforming Catalyst Performance	09/30/04	09/30/04	09/30/04	100%	Completed
2	Absorbent Performance	09/30/04	09/30/04	09/30/04	100%	Completed
3	Integrated Materials Performance	11/15/04	11/15/04	11/15/04	100%	Completed
4	Catalyst Production Scale up	11/15/04	6/15/05		90%	Halted
5	Integrated Catalyst Delivery	8/15/05	8/15/05		20%	Halted
6	Reactor concept modeling	07/06/04	07/06/04	2/1/05	100%	Completed
7	Reactor Installation	11/12/04	11/12/04	1/15/05	100%	Completed
8	Reactor Testing	08/03/05	08/03/05		75%	Halted
9	Reformer Installation	09/15/05	09/15/05		5%	Halted
10	Reformer Testing	10/01/06	10/1/06		0%	Halted

Table 14: Task Schedule

Project Spending and Estimate of Future Spending

Quarter	From	To	Estimated Federal Share of Outlays*	Actual Federal Share of Outlays	Estimated Recipient Share of Outlays*	Actual Recipient Share of Outlays	Estimated Cumulative
	10/1/2003	12/31/2004	$1,929,000	$1,959,820	$1,182,000	$1,201,000	$3,161,000
1Q05	1/1/2005	3/31/2005	$530,000	$401,060	$324,000	$245,991	$3,807,870
2Q05	4/1/2005	6/30/2005	$467,000	$520,596	$286,000	$319,074	$4,719,000
3Q05	7/31/2005	9/30/2005	$467,000	$455,853	$287,000	$279,393	$5,473,000
4Q05	10/1/2005	12/31/2005	$664,000		$407,000		$6,554,000
1Q06	1/1/2006	3/31/2006	$519,000		$318,000		$7,381,000
2Q06	4/1/2006	6/30/2006	$520,000		$318,000		$8,219,000
3Q06	7/31/2006	9/30/2006	$456,000		$280,000		$8,955,000
Totals	**10/1/2003**	**9/30/2006**	**$5,552,000**	$3,337,329	**$3,402,000**	$2,045,458	$8,955,000

Table 15: Project Spending and Estimate of Future Spending

NOMENCLATURE

ACM	Aspen Custom Modeler®
AER	Absorption Enhanced Reformer
ATR	Autothermal Reforming
CPO	Combustion Partial Oxidation
CTV	Chevron Technology Ventures
CSMP	Cabot Superior Micropowders
CE	Calcined Extrusions
ETC	Energy Technology Center
GHSV	Gas Hourly Space Velocities
HAZOP	Hazard and Operability Study
L/D	Length/Diameter
LHV	Lower Heating Valve
LSOP	Laboratory Standard Operating Procedure
Mass Spec	Mass Spectrometer
MCS	Modular Cooling System
MFB	Metal Fiber Burner
NI	National Instruments Compaq Field Point
PEM	Proton Exchange Membrane
PP	Post Processing
PPE	Pre-Procession Extrusion
PSA	Pressure Swing Absorption
PSD	Particle Size Distribution
RTC	Richmond Technology Center
S/C	Steam to Carbon Ratios
SEM	Scanning Electron Microscopy
SMR	Steam Methane Reforming
SSR	Absorption Enhanced Reforming
TC	Thermocouples
TCD	Thermal Conductivity Detector
TCin	Inlet Type K Thermocouple
TCout	Outlet Type K Thermocouple
TEM	Transmission Electron Microscopy
TES	Texaco Energy Systems, LLC
TGA	Thermogravimetric Analysis

WGS	Water-Gas Shift
XRD	X-Ray Diffraction

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APPENDICIES

Data reported and graphed for when H2 concentration $\geq$ 90%

APPENDIX A

CO2 Sorption Catalyst	*Composition CO_2 sorb*	*Post Processed Oven*	*Oven atmophere*	*Box Furnace Calcined (Air), °C*	*Extrudate Bulk Density, g/cc*	*Extrudate %Wt. Loss, CO2TGA*	*Crush strength, #/mm*	*Ramp Rate 10 C/min & Hold time, hr*	*Binder*
ECM 25-5003	CaO (100)	ITO	Air	750	0.76	3.2	3.9	3	CSMP Comp + 15%Al203
ECM 25-5008	CaO/MgO (80/20)	ITO	Air	750	0.87	23.5	4.9	3	CSMP Comp + 15%Al203
ECM 25-5019	CaO/Al2O3 (95/5)	ITO	Air	750	0.83	3.6	6.1	3	CSMP Comp + 15%Al203
ECM 25-5021	CaO/Al2O3 (90/10)	ITO	Air	750	0.75	20.0	2.9	3	CSMP Comp + 10%Al203
ECM 25-5022	CaO/Al2O3 (90/10)	ITO	Air	750	0.83	20.0	2.7	3	CSMP Comp + 15%Al203
*ECM 25-5029	CaO-Al203 (95/5)	ITO	Air	750	0.83	18.1	3.4	3	CSMP Comp + 15%Al203
*ECM25-5036	CaO-Al203 (90/10)	ITO	Air	750	0.93	25.0	6.7	3	CSMP Comp + 15%Al203
ECM25-5061C300	CaO/Al2O3 (90/10)	ITO	Air	300	1.00	30.5	6.4	3	CSMP Comp + 15%Al203
ECM25-5061C500	CaO/Al2O3 (90/10)	ITO	Air	500	1.00	28.9	7.4	3	CSMP Comp + 15%Al203
ECM25-5061C750	CaO/Al2O3 (90/10)	ITO	Air	750	0.90	15.5	5.6	3	CSMP Comp + 15%Al203
ECM25-5061C800	CaO/Al2O3 (90/10)	ITO	Air	800	0.70	4.8	6.1	3	CSMP Comp + 15%Al203
ECM259-002-2C	CaO/Al2O3 (90/10)	Rotary Calciner	N2	750	0.89	23.0	6.5	66 min	CSMP Comp + 15%Al203
ECM259-011C	CaO/Al2O3 (90/10)	Rotary Calciner	N2	750	0.80	16.0	5.3	33 min	CSMP Comp + 15%Al203
*ECM259-012C	CaO/Al2O3 (90/10)	ITO	Air	750	0.82	21.0	6.4	3	CSMP Comp + 15%Al203
*ECM259-013C	CaO/Al2O3 (90/10)	ITO	Air	750	0.76	9.0	5.2	3	CSMP Comp + 15%Al203
*ECM259-018C800	CaO/Al2O3 (90/10)	Rotary Calciner	N2	800	0.72	6.2			CSMP Comp + 15%Al203

APPENDIX B

Carbon Conversion, Water Gas Shift and CO2 Fixing Efficiency Calculations

The fundamental reactions and equations follows assuming one mole of CH_4 is reformed in the presence of excess H_2O and CaO. Further assume that x is the fraction of CH_4 that is reformed, y is the fraction of CO that is shifted to CO_2, and z is the fraction of CO_2 that is fixed by reaction with CaO. Then:

Steam Reforming: $CH_4 + H_2O \Rightarrow xCO + 3xH_2 + (1-x)CH_4 + (1-x)H_2O$

Water Gas Shift $xCO + H_2O \Rightarrow xyCO_2 + xyH_2 + (1-y)xCO + (1-xy)H_2O$

Carbonation: $CaO + xyCO_2 \Rightarrow xyz\ CaCO_3 + (1-xyz)CaO + (1-z)xyCO_2$

The dry gas compositions are given as (3x+xy) moles of H_2, (1-x) moles of CH_4, (1-y)x moles of CO, and (1-z)xy moles of CO_2. Measured concentration of these four gases in the reformate stream can be used to calculate the conversion efficiencies to rank the sorbents. Mole ratio equations of CH_4, CO and CO_2 with respect to H_2 are solved simultaneously to obtain x,y, and z. The variables x, y and z are calculated as functions of the ratios of these gases due to inert gases such as N_2, Argon (Ar) and others in the reformate stream. Since

$$[CO]/[H_2] = (1-y)x/(x(3+Y)$$

$$[CH_4]/[H_2] = (1-x)/(x(3+y))$$

$$[CO_2]/[H_2] = (1-z)xy/(x(3+y))$$

It follows the water gas shift conversion efficiency (WGS) is given by:

$$y = (1-3[CO]/[H_2])/(1+[CO]/[H_2])$$

The steam methane reforming reaction (CC) is given by:

$$x = (1+(3+y)[CH4]/[H2])^{-1}$$

Finally, the carbon dioxide fixing efficiency (CF) is given by:

$$z = 1 - ((3+y)[CO2]/[H2])/y$$

APPENDIX C

CO_2 Sorption Catalyst Reforming Catalyst: 0.5% rhodium on Alumina	C2873-29-32 CSMP C2873-19-31	C2873-29-34 CSMP C2873-19-31	C2873-30-25 CSMP C2873-19-31	C2873-31-33 Engelhard Escat 326 (0.5%Rh on Alumina)	C2873-32-30 Engelhard Escat 326 (0.5%Rh on Alumina)
Composition CO_2 sorb	CaO/MgO (50:50)	CaO/MgO (50:50)	CaO/MgO (50:50)	CaO, 5%CaTiO3	CaOMgO-CaTiO3 (3:1 at.)
Binder	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3
Batch No.	HCM178138E	HCM178138E	PCM178033A	HCY178138B	HCZ178132C
Extruded by	RTC	RTC	RTC	RTC	RTC
Oven Atmosphere	Air	Air	Air	Air	Air
Calcined, C	500C	750C	500C	750C	750C
Wt. CO_2 extrudate, g	19.53	19.53	20.40	23.08	20.07
Vol. CO_2 extrudate, cc	32.6	32.4	30.0	31.0	35.5
density CO2, g/cc	0.6	0.6	0.7	0.7	0.6
Wt. SMR Cat., g	3.9	3.9	4.3	4.6	4.0
Vol. SMR Cat., cc	6.5	6.5	6.6	7.0	7.0
density SMR, g/cc	0.6			0.7	0.6
Total Bed wt., g	23.44	23.44	24.72	27.69	24.07
Total Bed Vol., ml	39.1	38.9	36.6	38.0	42.5
Reactor	R1	R1	R1	R1	R1
S/C	3	3	3	3	3
GHSV, hr-1	390	390	390	390	390
Reforming, °C	600	600	600	600	600
Calcination, °C	750	750	750	750	800
Pressure, atm	1	1	1	1	1
Crushed catalyst and sifted between 30 and 20 mesh, to achieve approximately 1/10 diameter of bed. No layers, mixed Note: SMP C2873-19-31 = SMP	Crushed	Crushed	Crushed	Crushed	Extrudate

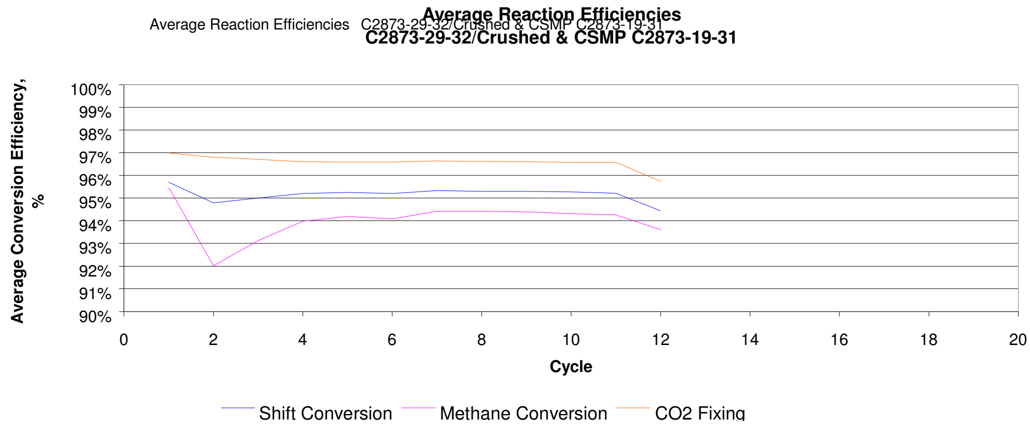
CO_2 Sorption Catalyst Reforming Catalyst: 0.5% rhodium on Alumina	**C2873-33-33 Engelhard Escat 326 (0.5%Rh on Alumina)**	**C2873-34-30 Engelhard Escat 326 (0.5%Rh on Alumina)**	**C2873-35-31 CSMP C2873-19-31**	**C2873-50-24 CSMP C2873-19-31**	**C2873-50-26 CSMP C2873-19-31**	**C3021-34-34 Engelhard Escat 326 (0.5%Rh on Alumina)**
Composition CO_2 sorb	CaO-CaTiO3 (3:1 at.)	Ca Oxalate, 5wt% Al2O3	Ca Oxalate, 5wt% Al2O3	CaO/MgO (80:20)	CaO/MgO (80:20)	CaO/MgO (55:45)
Binder	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3	CSMP Comp.+15% Al2O3
Batch No.	HCY178138C	PCL178019A	PCL178019C	HCM178157D	HCM178157D	HCM178165E
Extruded by	RTC	RTC	RTC	RTC	RTC	RTC
Oven Atmosphere	Air	Air	Air	Air	Air	Air
Calcined, C	750C	750C	750C	750C	750C	500C
Wt. CO_2 extrudate, g	20.09	19.59	19.52	19.56	19.55	25.01
Vol. CO_2 extrudate, cc	34.0	31.6	22.4	34.1	35.0	33.7
density CO2, g/cc	0.6	0.6	0.9	0.6	0.6	0.7
Wt. SMR Cat., g	4.0	4.0	4.0	3.9	3.9	5.0
Vol. SMR Cat., cc	6.5	6.4	4.6	6.8	7.0	9.0
density SMR, g/cc	0.6	0.6	0.9	0.6	0.6	0.6
Total Bed wt., g	24.09	23.56	23.50	23.49	23.48	30.01
Total Bed Vol., ml	40.5	38.0	26.9	40.9	42.0	42.7
Reactor	R1	R1	R1	R1	R1	R2
S/C	3	3	3	3	3	3
GHSV, hr-1	390	390	390	390	390	390
Reforming, °C	600	600	600	600	600	600
Calcination, °C	800	750	750	750	750	750
Pressure, atm	1	1	1	1	1	1
Crushed catalyst and sifted between 30 and 20 mesh, to achieve approximately 1/10 diameter of bed. No layers, mixed Note: SMP C2873-19-31 = SMP	Extrudate	Crushed	Crushed	Crushed	Crushed	Extrudate

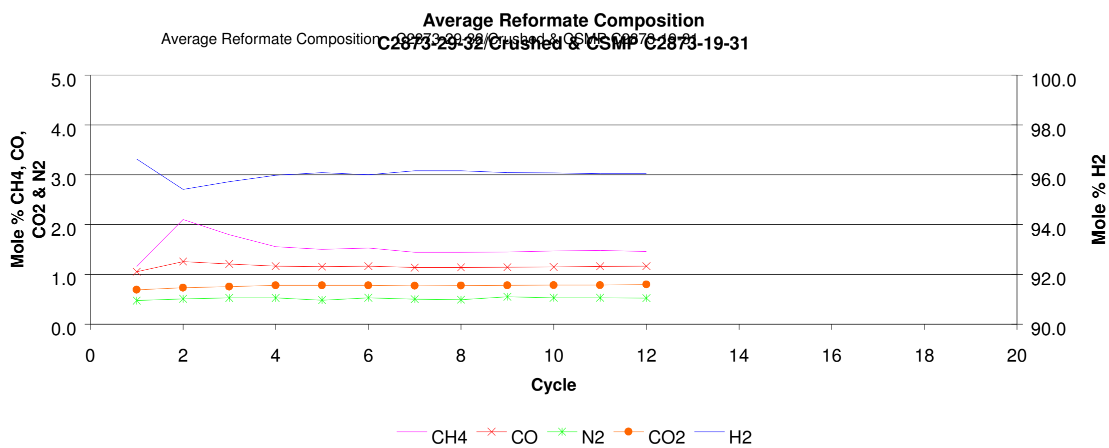
CO_2 Sorption Catalyst	C2873-29-32/Crushed
Reforming Catalyst: 0.5% rhodium or	CSMP C2873-19-31
Composition CO_2 sorb	CaO/MgO (50:50)
Binder	15% Al2O3
Batch No.	HCM178138E
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	500C

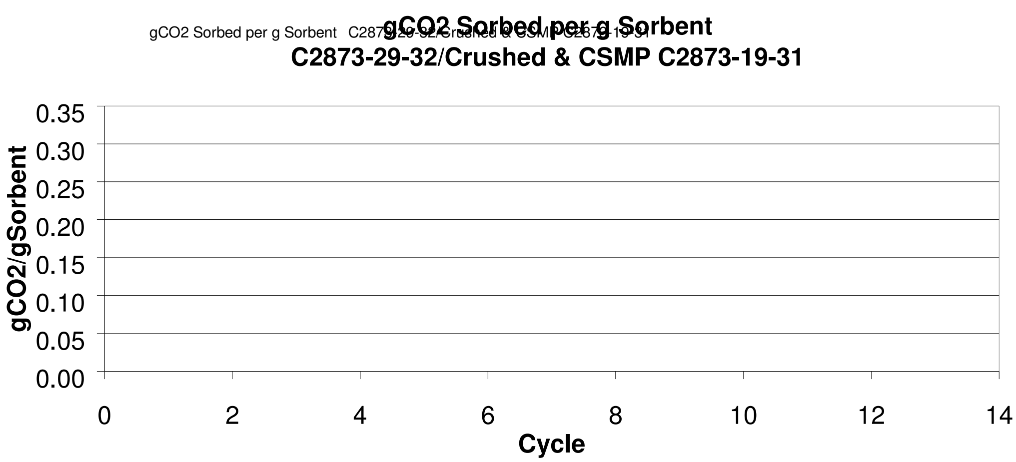
Wt. CO2 extrudate, g	19.53
Vol. CO2 extrudate, cc	32.6
Density CO2, g/cc	0.6
Wt. SMR Cat., g	3.91
Vol. SMR Cat., cc	6.5
Density SMR, g/cc	0.6
Total Bed Wt., g	23.44
Total Bed Vol., ml	39.1

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	96.6	1.2	1.0	0.5	0.7	4624.97	95.7%	95.5%	97.0%	26.49	0.0056	0.15
2	95.4	2.1	1.3	0.5	0.7	4745.64	94.8%	92.0%	96.8%	26.57	0.0054	0.14
3	95.7	1.8	1.2	0.5	0.8	4855.15	95.0%	93.1%	96.7%	24.34	0.0055	0.13
4	96.0	1.6	1.2	0.5	0.8	4960.67	95.2%	94.0%	96.6%	23.29	0.0055	0.13
5	96.1	1.5	1.2	0.5	0.8	5068.90	95.2%	94.2%	96.6%	22.38	0.0055	0.12
6	96.0	1.5	1.2	0.5	0.8	5178.76	95.2%	94.1%	96.6%	21.80	0.0055	0.12
7	96.2	1.4	1.1	0.5	0.8	5288.53	95.3%	94.4%	96.6%	21.16	0.0055	0.12
8	96.2	1.4	1.1	0.5	0.8	5398.43	95.3%	94.4%	96.6%	20.90	0.0055	0.12
9	96.1	1.4	1.1	0.5	0.8	5508.69	95.3%	94.4%	96.6%	20.30	0.0055	0.11
10	96.1	1.5	1.1	0.5	0.8	5618.69	95.3%	94.3%	96.6%	20.01	0.0055	0.11
11	96.0	1.5	1.2	0.5	0.8	5728.68	95.2%	94.3%	96.6%	19.76	0.0055	0.11
12	96.0	1.5	1.2	0.5	0.8	5838.82	94.4%	93.6%	95.7%	19.77	0.0055	0.11


Average Reaction Efficiencies C2873-29-32/Crushed & CSMP C2873-19-31
Average Reaction Efficiencies
C2873-29-32/Crushed & CSMP C2873-19-31
Average Conversion Efficiency, %
100%
99%
98%
97%
96%
95%
94%
93%
92%
91%
90%
0
2
4
6
8
10
12
14
16
18
20
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C2873-29-32/Crushed & CSMP C2873-19-31
Average Reformate Composition
C2873-29-32/Crushed & CSMP C2873-19-31
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0
2
4
6
8
10
12
14
16
18
20
Cycle
CH4
CO
N2
CO2
H2

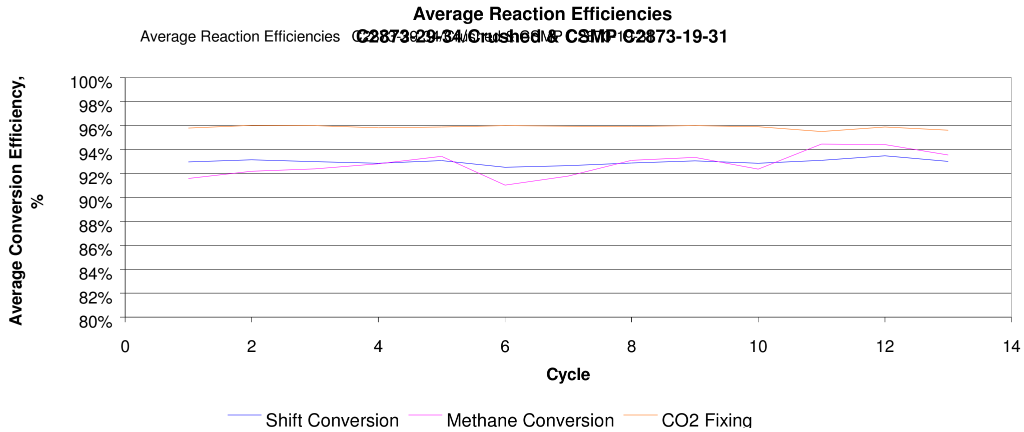

gCO2 Sorbed per g Sorbent C2873-29-32/Crushed & CSMP C2873-19-31
gCO2 Sorbed per g Sorbent
C2873-29-32/Crushed & CSMP C2873-19-31
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
14
Cycle

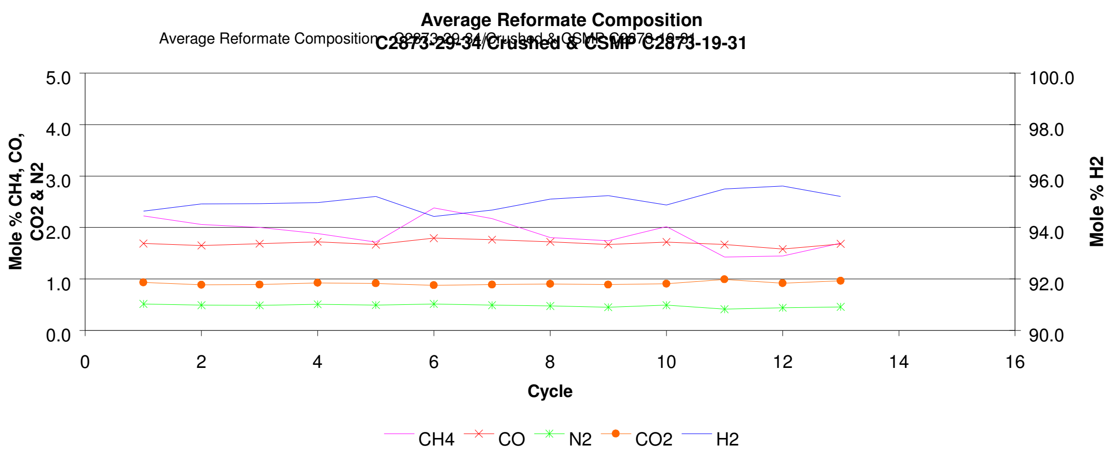
CO_2 Sorption Catalyst	C2873-29-34/Crushed
Reforming Catalyst: 0.5% rhodium o	CSMP C2873-19-31
Composition CO_2 sorb	CaO/MgO (50:50)
Binder	15% Al2O3
Batch No.	HCM178138E
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750C

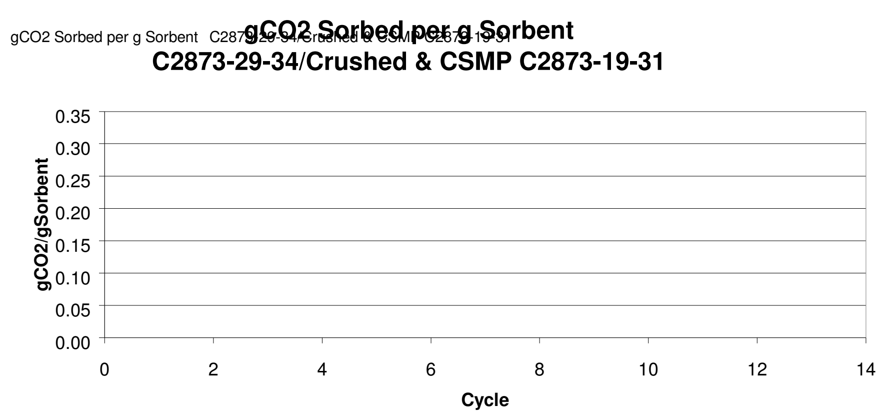
Wt. CO2 extrudate, g	19.53
Vol. CO2 extrudate, cc	32.4
Density CO2, g/cc	0.6
Wt. SMR Cat., g	3.91
Vol. SMR Cat., cc	6.5
Density SMR, g/cc	
Total Bed Wt., g	23.44
Total Bed Vol., ml	38.9

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	94.6	2.2	1.7	0.5	0.9	1063.46	93.0%	91.6%	95.8%	39.32	0.0052	0.20
2	94.9	2.1	1.7	0.5	0.9	1198.09	93.1%	92.2%	96.0%	37.34	0.0053	0.20
3	94.9	2.0	1.7	0.5	0.9	1333.36	93.0%	92.4%	96.0%	36.90	0.0052	0.19
4	95.0	1.9	1.7	0.5	0.9	2028.53	92.9%	92.8%	95.8%	39.68	0.0053	0.21
5	95.2	1.7	1.7	0.5	0.9	2152.47	93.1%	93.4%	95.9%	36.81	0.0053	0.20
6	94.4	2.4	1.8	0.5	0.9	2278.43	92.5%	91.0%	96.0%	36.57	0.0052	0.19
7	94.7	2.2	1.8	0.5	0.9	2403.32	92.7%	91.8%	96.0%	34.59	0.0052	0.18
8	95.1	1.8	1.7	0.5	0.9	2527.22	92.9%	93.1%	95.9%	33.43	0.0053	0.18
9	95.2	1.7	1.7	0.5	0.9	2652.07	93.1%	93.4%	96.0%	32.01	0.0053	0.17
10	94.9	2.0	1.7	0.5	0.9	2777.58	92.9%	92.4%	95.9%	32.15	0.0052	0.17
11	95.5	1.4	1.7	0.4	1.0	2902.64	93.1%	94.5%	95.5%	31.56	0.0054	0.17
12	95.6	1.4	1.6	0.4	0.9	3027.36	93.5%	94.4%	95.9%	30.46	0.0054	0.16
13	95.2	1.7	1.7	0.5	1.0	3153.05	93.0%	93.5%	95.6%	30.63	0.0053	0.16


Average Reaction Efficiencies
C2873-29-34/Crushed & CSMP C2873-19-31
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
2
4
6
8
10
12
14
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition
C2873-29-34/Crushed & CSMP C2873-19-31
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
2
4
6
8
10
12
14
16
Cycle
CH4
CO
N2
CO2
H2

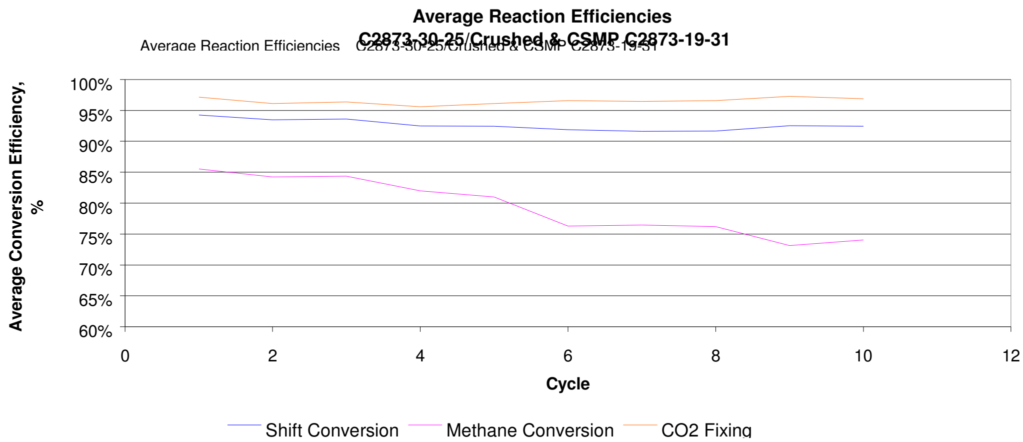

gCO2 Sorbed per g Sorbent
C2873-29-34/Crushed & CSMP C2873-19-31
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
14
Cycle

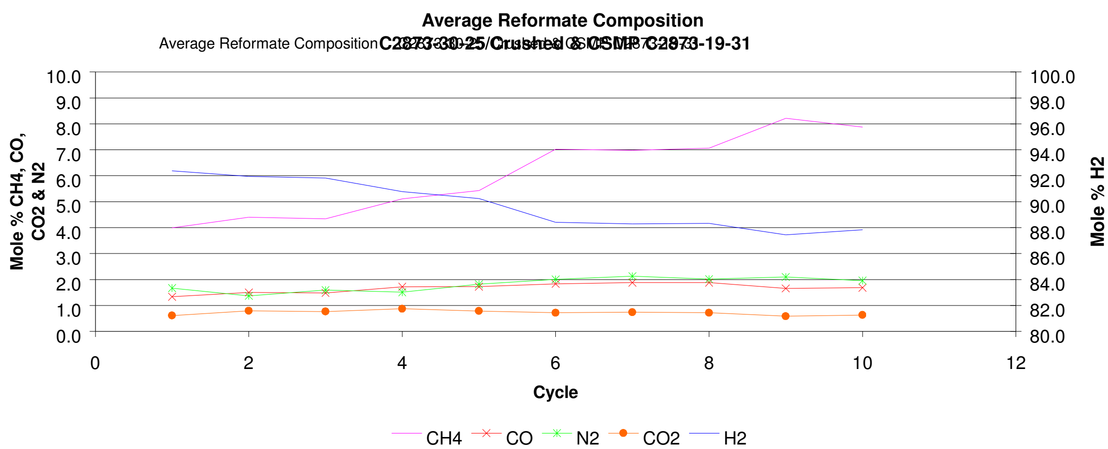
CO_2 Sorption Catalyst	C2873-30-25/Crushed
Reforming Catalyst: 0.5% rhodium o	CSMP C2873-19-31
Composition CO_2 sorb	CaO/MgO (50:50)
Binder	15% Al2O3
Batch No.	PCM178033A
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	500C

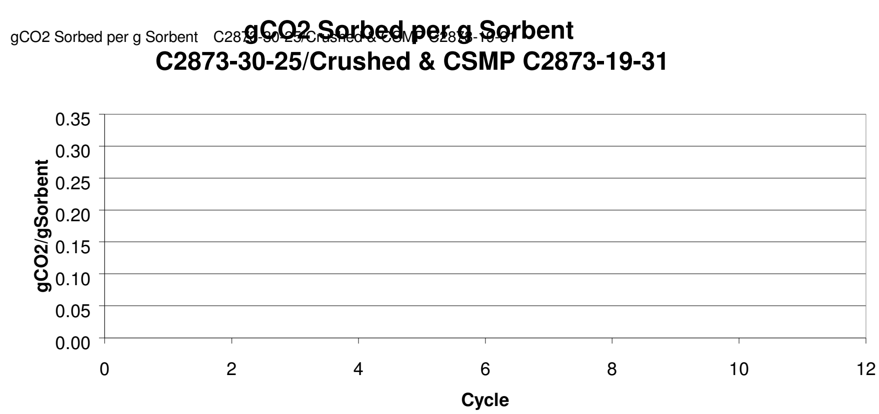
Wt. CO2 extrudate, g	20.40
Vol. CO2 extrudate, cc	30.0
Density CO2, g/cc	0.7
Wt. SMR Cat., g	4.32
Vol. SMR Cat., cc	6.6
Density SMR, g/cc	
Total Bed Wt., g	24.72
Total Bed Vol., ml	36.6

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	qCO2/qSorb
1	92.4	4.0	1.3	1.7	0.6	228.91	94.3%	85.5%	97.1%	35.60	0.0044	0.16
2	91.9	4.4	1.5	1.4	0.8	398.93	93.5%	84.2%	96.1%	34.03	0.0043	0.15
3	91.8	4.3	1.5	1.6	0.8	557.65	93.6%	84.4%	96.4%	31.50	0.0043	0.14
4	90.8	5.1	1.7	1.5	0.9	717.79	92.5%	82.0%	95.6%	31.57	0.0041	0.13
5	90.2	5.4	1.7	1.8	0.8	877.22	92.4%	81.0%	96.1%	30.18	0.0041	0.12
6	88.4	7.0	1.8	2.0	0.7	1037.28	91.9%	76.3%	96.6%	30.37	0.0038	0.12
7	88.3	7.0	1.9	2.1	0.7	1196.79	91.6%	76.5%	96.5%	29.00	0.0038	0.11
8	88.3	7.1	1.9	2.0	0.7	1356.13	91.7%	76.2%	96.6%	27.81	0.0038	0.11
9	87.4	8.2	1.7	2.1	0.6	1501.88	92.5%	73.1%	97.2%	25.94	0.0037	0.10
10	87.8	7.9	1.7	2.0	0.6	1661.08	92.4%	74.1%	96.9%	24.95	0.0038	0.09


Average Reaction Efficiencies
C2873-30-25/Crushed & CSMP C2873-19-31
Average Reaction Efficiencies C2873-30-25/Crushed & CSMP C2873-19-31
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
65%
60%
0
2
4
6
8
10
12
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition
Average Reformate Composition C2873-30-25/Crushed & CSMP C2873-19-31
C2873-30-25/Crushed & CSMP C2873-19-31
Mole % CH4, CO, CO2 & N2
Mole % H2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
88.0
86.0
84.0
82.0
80.0
0
2
4
6
8
10
12
Cycle
CH4
CO
N2
CO2
H2

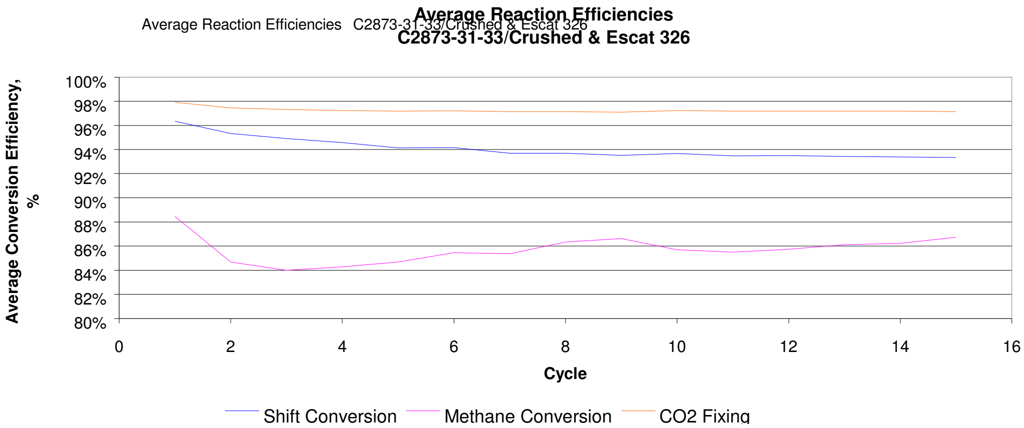

gCO2 Sorbed per g Sorbent C2873-30-25/Crushed & CSMP C2873-19-31
gCO2 Sorbed per g Sorbent
C2873-30-25/Crushed & CSMP C2873-19-31
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
Cycle

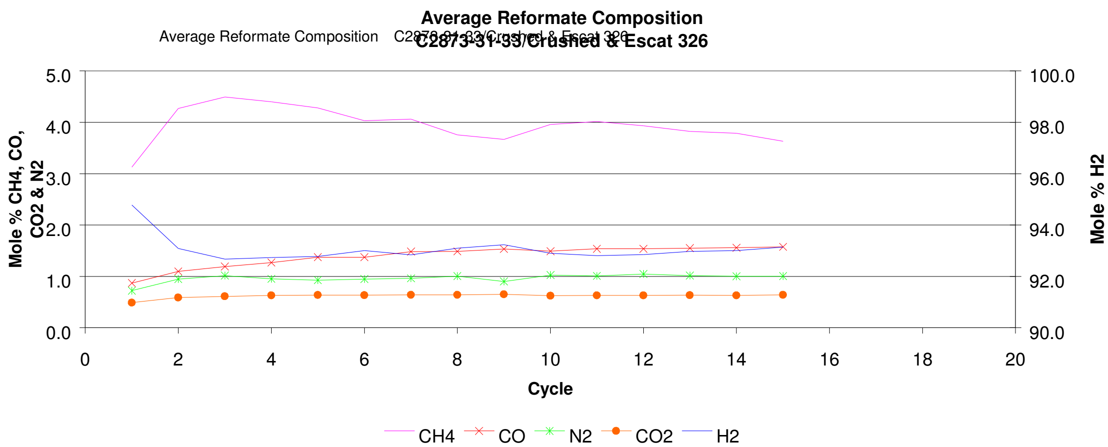
CO_2 Sorption Catalyst	C2873-31-33/Crushed
Reforming Catalyst: 0.5% rhodium or	Escat 326
Composition CO_2 sorb	CaO, 5%CaTiO3
Binder	15% Al2O3
Batch No.	HCY178138B
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750C

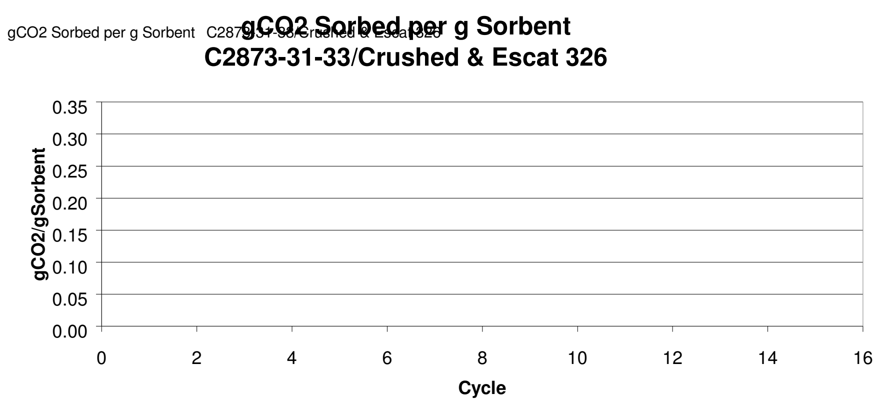
Wt. CO2 extrudate, g	23.08
Vol. CO2 extrudate, cc	31.0
Density CO2, g/cc	0.7
Wt. SMR Cat., g	4.61
Vol. SMR Cat., cc	7.0
Density SMR, g/cc	0.7
Total Bed Wt., g	27.69
Total Bed Vol., ml	38.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CE	Cycle Time	S	gCO2/gSorb
1	94.8	3.1	0.9	0.7	0.5	385.77	96.4%	88.5%	97.9%	59.88	0.0045	0.27
2	93.1	4.3	1.1	0.9	0.6	556.19	95.3%	84.7%	97.5%	60.13	0.0042	0.26
3	92.7	4.5	1.2	1.0	0.6	722.45	94.9%	84.0%	97.3%	53.88	0.0042	0.23
4	92.7	4.4	1.3	1.0	0.6	890.05	94.6%	84.3%	97.2%	46.41	0.0042	0.19
5	92.8	4.3	1.4	0.9	0.6	1058.82	94.1%	84.7%	97.2%	45.26	0.0042	0.19
6	93.0	4.0	1.4	0.9	0.6	1226.54	94.2%	85.5%	97.2%	40.20	0.0042	0.17
7	92.8	4.1	1.5	1.0	0.6	1396.25	93.7%	85.3%	97.2%	41.11	0.0042	0.17
8	93.1	3.8	1.5	1.0	0.6	1565.20	93.7%	86.3%	97.1%	39.00	0.0042	0.17
9	93.2	3.7	1.5	0.9	0.7	1734.61	93.5%	86.6%	97.1%	37.94	0.0042	0.16
10	92.9	4.0	1.5	1.0	0.6	1903.52	93.7%	85.7%	97.2%	34.91	0.0042	0.15
11	92.8	4.0	1.5	1.0	0.6	2073.09	93.5%	85.5%	97.2%	34.80	0.0042	0.15
12	92.8	3.9	1.5	1.0	0.6	2242.49	93.5%	85.7%	97.2%	32.77	0.0042	0.14
13	93.0	3.8	1.6	1.0	0.6	2412.04	93.4%	86.1%	97.2%	32.83	0.0042	0.14
14	93.0	3.8	1.6	1.0	0.6	2581.95	93.4%	86.2%	97.2%	31.66	0.0042	0.13
15	93.1	3.6	1.6	1.0	0.6	2751.33	93.3%	86.7%	97.1%	31.76	0.0042	0.13


Average Reaction Efficiencies C2873-31-33/Crushed & Escat 326
Average Reaction Efficiencies
C2873-31-33/Crushed & Escat 326
Average Conversion Efficiency, %
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C2873-31-33/Crushed & Escat 326
Average Reformate Composition
C2873-31-33/Crushed & Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
Cycle
CH4
CO
N2
CO2
H2

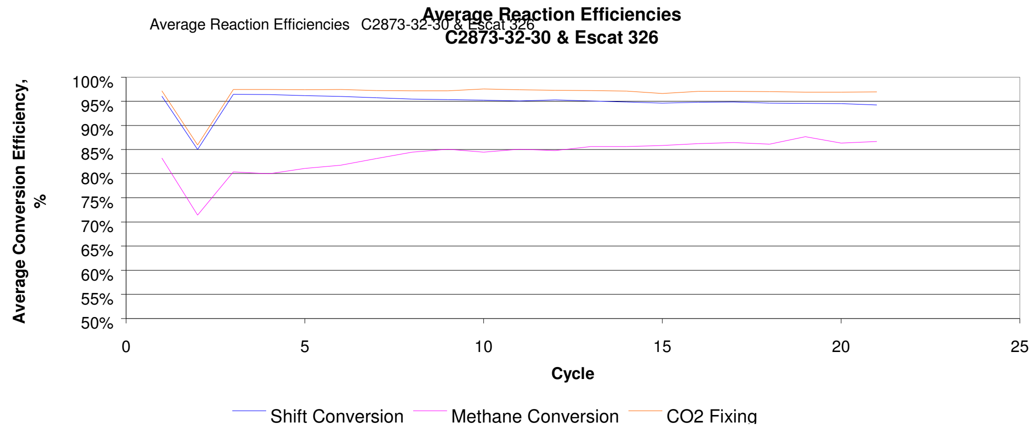

gCO2 Sorbed per g Sorbent C2873-31-33/Crushed & Escat 326
gCO2 Sorbed per g Sorbent
C2873-31-33/Crushed & Escat 326
gCO2/gSorbent
Cycle

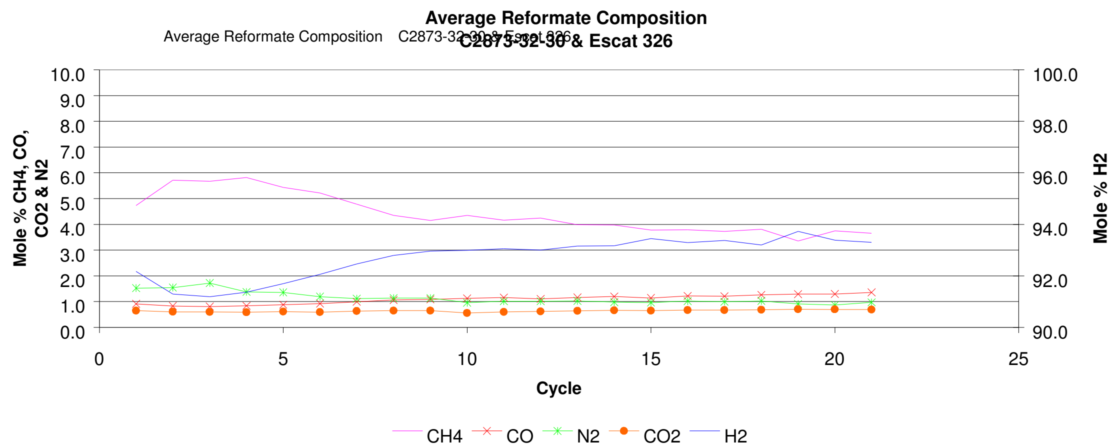
CO_2 Sorption Catalyst	C2873-32-30
Reforming Catalyst: 0.5% rhodium o	Escat 326
Composition CO_2 sorb	CaOMgO-CaTiO3
Binder	15% Al2O3
Batch No.	HCZ178132C
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750C

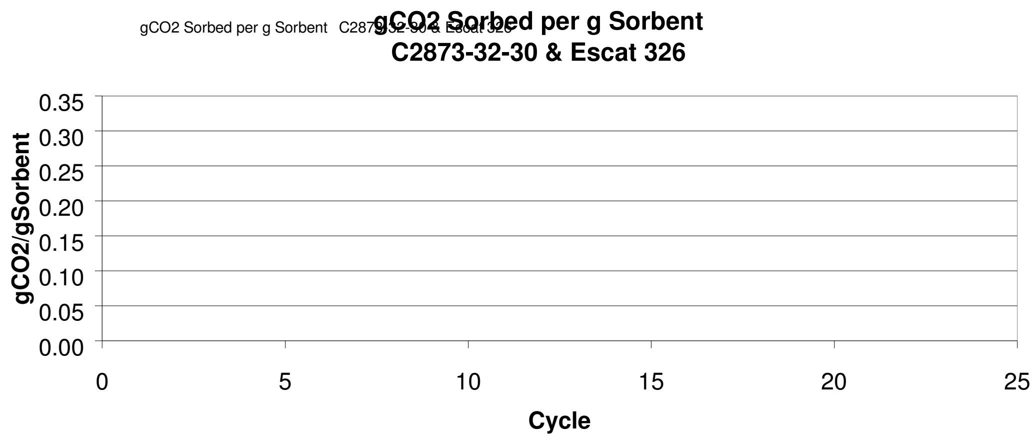
Wt. CO2 extrudate, g	20.07
Vol. CO2 extrudate, cc	35.5
Density CO2, g/cc	0.6
Wt. SMR Cat., g	4.00
Vol. SMR Cat., cc	7.0
Density SMR, g/cc	0.6
Total Bed Wt., g	24.07
Total Bed Vol., ml	42.5

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	92.2	4.7	0.9	1.5	0.6	952.86	96.1%	83.2%	97.2%	29.64	0.0048	0.14
2	91.3	5.7	0.8	1.5	0.6	1144.22	85.0%	71.4%	85.9%	11.39	0.0042	0.05
3	91.2	5.7	0.8	1.7	0.6	1314.54	96.5%	80.4%	97.4%	12.12	0.0047	0.06
4	91.4	5.8	0.8	1.4	0.6	1488.74	96.4%	80.0%	97.5%	20.78	0.0047	0.10
5	91.7	5.4	0.9	1.4	0.6	1662.30	96.2%	81.1%	97.4%	27.86	0.0047	0.13
6	92.1	5.2	0.9	1.2	0.6	1834.04	96.0%	81.7%	97.4%	31.12	0.0047	0.15
7	92.5	4.8	1.0	1.1	0.6	2005.16	95.7%	83.1%	97.3%	32.40	0.0048	0.16
8	92.8	4.3	1.1	1.1	0.6	2174.83	95.4%	84.5%	97.2%	34.00	0.0049	0.17
9	93.0	4.2	1.1	1.1	0.7	2344.44	95.4%	85.1%	97.2%	32.50	0.0049	0.16
10	93.0	4.3	1.1	1.0	0.6	9384.14	95.2%	84.5%	97.6%	34.29	0.0049	0.17
11	93.1	4.2	1.2	1.0	0.6	9553.77	95.1%	85.1%	97.4%	32.84	0.0049	0.16
12	93.0	4.2	1.1	1.0	0.6	9693.44	95.3%	84.8%	97.3%	32.08	0.0049	0.16
13	93.2	4.0	1.2	1.0	0.6	9833.27	95.0%	85.6%	97.2%	30.95	0.0049	0.15
14	93.2	4.0	1.2	1.0	0.7	9972.98	94.9%	85.6%	97.1%	30.98	0.0049	0.15
15	93.4	3.8	1.1	1.0	0.7	10111.80	94.7%	85.8%	96.6%	29.28	0.0049	0.14
16	93.3	3.8	1.2	1.0	0.7	10252.16	94.8%	86.2%	97.1%	29.16	0.0049	0.14
17	93.4	3.7	1.2	1.0	0.7	10391.52	94.8%	86.4%	97.1%	28.57	0.0049	0.14
18	93.2	3.8	1.3	1.0	0.7	10531.76	94.6%	86.1%	97.0%	27.78	0.0049	0.14
19	93.7	3.4	1.3	0.9	0.7	10671.26	94.6%	87.7%	96.9%	25.99	0.0050	0.13
20	93.4	3.7	1.3	0.9	0.7	10811.77	94.5%	86.4%	96.9%	24.34	0.0049	0.12
21	93.3	3.7	1.4	1.0	0.7	10951.17	94.2%	86.6%	96.9%	25.96	0.0049	0.13


Average Reaction Efficiencies C2873-32-30 & Escat 326
Average Reaction Efficiencies
C2873-32-30 & Escat 326
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
65%
60%
55%
50%
0
5
10
15
20
25
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C2873-32-30 & Escat 326
Average Reformate Composition
C2873-32-30 & Escat 326
Mole % CH4, CO, CO2 & N2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
5
10
15
20
25
Cycle
CH4
CO
N2
CO2
H2

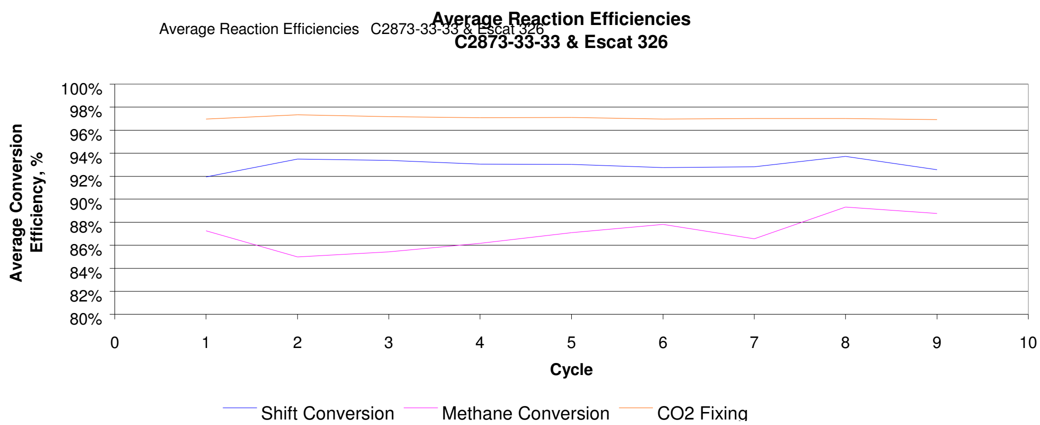

gCO2 Sorbed per g Sorbent C2873-32-30 & Escat 326
gCO2 Sorbed per g Sorbent
C2873-32-30 & Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
Cycle

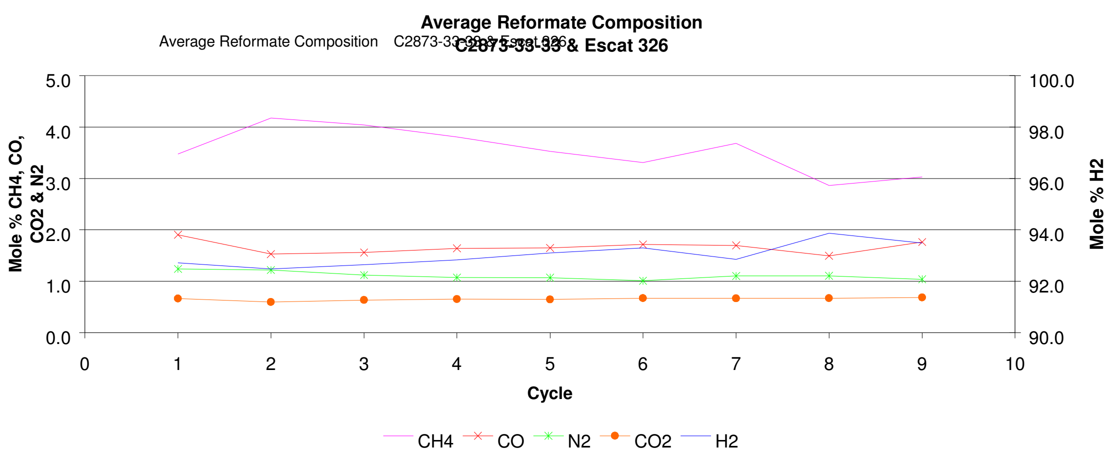
CO_2 Sorption Catalyst	C2873-33-33
Reforming Catalyst: 0.5% rhodium on	Escat 326
Composition CO_2 sorb	CaO-CaTiO3 (3:1 at.)
Binder	15% Al2O3
Batch No.	HCY178138C
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750C

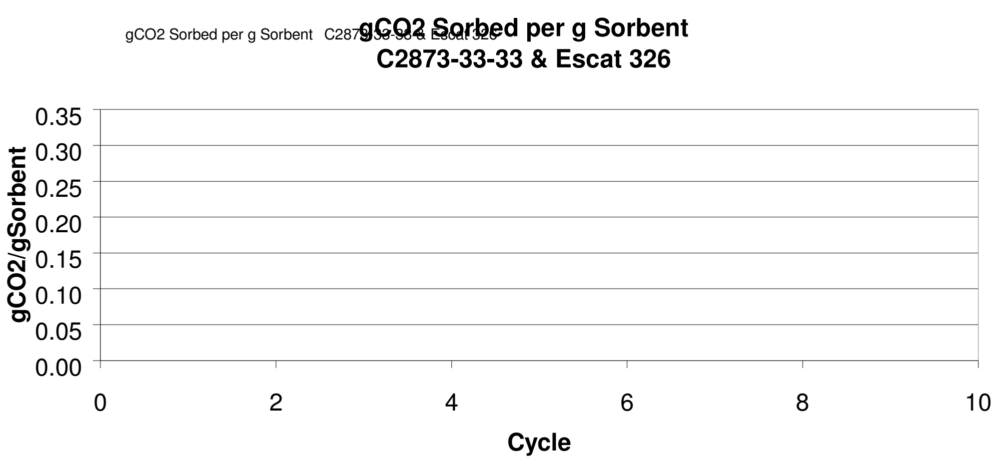
Wt. CO2 extrudate, g	20.09
Vol. CO2 extrudate, cc	34.0
Density CO2, g/cc	0.6
Wt. SMR Cat., g	4.00
Vol. SMR Cat., cc	6.5
Density SMR, g/cc	0.6
Total Bed Wt., g	24.09
Total Bed Vol., ml	40.5

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	92.7	3.5	1.9	1.2	0.7	2951.31	91.9%	87.3%	97.0%	22.50	0.0046	0.10
2	92.5	4.2	1.5	1.2	0.6	3129.31	93.5%	85.0%	97.3%	21.15	0.0045	0.10
3	92.6	4.0	1.6	1.1	0.6	3310.12	93.4%	85.4%	97.2%	22.00	0.0046	0.10
4	92.8	3.8	1.6	1.1	0.7	3490.27	93.0%	86.2%	97.1%	23.36	0.0046	0.11
5	93.1	3.5	1.6	1.1	0.6	3670.57	93.0%	87.1%	97.1%	23.39	0.0046	0.11
6	93.3	3.3	1.7	1.0	0.7	3850.47	92.8%	87.8%	97.0%	24.21	0.0046	0.11
7	92.9	3.7	1.7	1.1	0.7	4030.03	92.8%	86.6%	97.0%	22.09	0.0046	0.10
8	93.9	2.9	1.5	1.1	0.7	4208.43	93.7%	89.3%	97.0%	22.86	0.0048	0.11
9	93.5	3.0	1.8	1.0	0.7	4390.51	92.6%	88.8%	96.9%	23.40	0.0047	0.11


Average Reaction Efficiencies C2873-33-33 & Escat 326
Average Reaction Efficiencies
C2873-33-33 & Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
1
2
3
4
5
6
7
8
9
10
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition
Average Reformate Composition C2873-33-33 & Escat 326
C2873-33-33 & Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
1
2
3
4
5
6
7
8
9
10
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent C2873-33-33 & Escat 326
gCO2 Sorbed per g Sorbent
C2873-33-33 & Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
Cycle

CO_2 Sorption Catalyst	C2873-34-30/Crushed
Reforming Catalyst: 0.5% rhodium or	C2873-19-31
Composition CO_2 sorb	Ca Oxalate, 5wt% Al2O3
Binder	15% Al2O3
Batch No.	PCL178019A
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750C

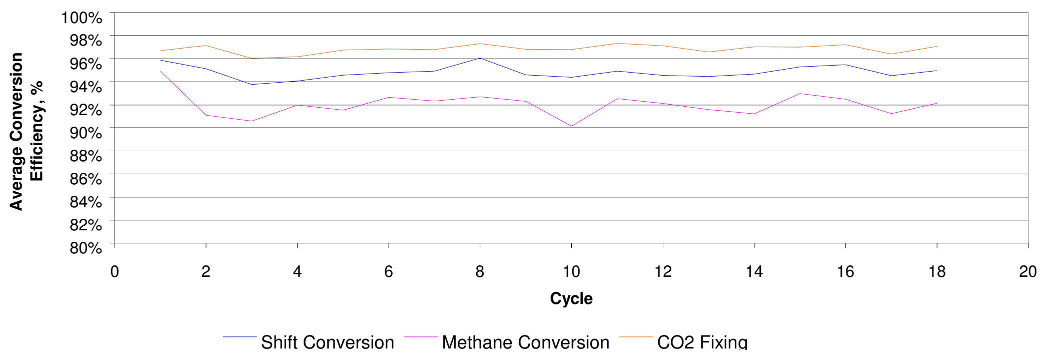
Wt. CO2 extrudate, g	19.59
Vol. CO2 extrudate, cc	31.6
Density CO2, g/cc	0.6
Wt. SMR Cat., g	3.97
Vol. SMR Cat., cc	6.4
Density SMR, g/cc	0.6
Total Bed Wt., g	23.56
Total Bed Vol., ml	38.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	96.6	1.3	1.0	0.3	0.8	1472.58	95.9%	94.9%	96.7%	57.36	0.0055	0.31
2	95.3	2.4	1.2	0.5	0.7	1643.77	95.1%	91.1%	97.1%	59.01	0.0052	0.31
3	95.2	2.3	1.3	0.5	0.7	1805.52	93.8%	90.6%	96.0%	59.85	0.0052	0.31
4	95.6	2.0	1.3	0.4	0.7	1965.41	94.1%	92.0%	96.2%	57.26	0.0052	0.30
5	95.3	2.2	1.3	0.4	0.7	2126.27	94.6%	91.5%	96.8%	55.97	0.0052	0.29
6	95.7	1.9	1.3	0.4	0.7	2286.19	94.8%	92.7%	96.8%	53.88	0.0053	0.28
7	95.6	2.0	1.2	0.4	0.7	2446.77	94.9%	92.3%	96.8%	53.20	0.0053	0.28
8	96.0	1.9	1.0	0.5	0.6	2602.58	96.1%	92.7%	97.3%	51.07	0.0054	0.27
9	95.5	2.0	1.3	0.4	0.7	2768.83	94.6%	92.3%	96.8%	50.89	0.0053	0.27
10	94.8	2.6	1.3	0.5	0.7	2930.26	94.4%	90.2%	96.8%	51.66	0.0051	0.26
11	95.8	2.0	1.2	0.4	0.6	203.05	94.9%	92.6%	97.3%	50.26	0.0053	0.27
12	95.5	2.1	1.3	0.4	0.6	405.96	94.6%	92.1%	97.1%	52.50	0.0053	0.28
13	95.3	2.2	1.3	0.4	0.8	567.93	94.5%	91.6%	96.6%	54.50	0.0052	0.28
14	95.3	2.3	1.3	0.5	0.7	727.51	94.7%	91.2%	97.0%	52.17	0.0052	0.27
15	96.0	1.8	1.1	0.4	0.7	887.82	95.3%	93.0%	97.0%	50.84	0.0053	0.27
16	95.9	2.0	1.1	0.4	0.6	1048.08	95.5%	92.5%	97.2%	47.61	0.0053	0.25
17	95.1	2.3	1.3	0.4	0.8	1211.56	94.5%	91.3%	96.4%	53.11	0.0052	0.27
18	95.7	2.1	1.2	0.4	0.7	1371.00	95.0%	92.1%	97.1%	49.32	0.0053	0.26

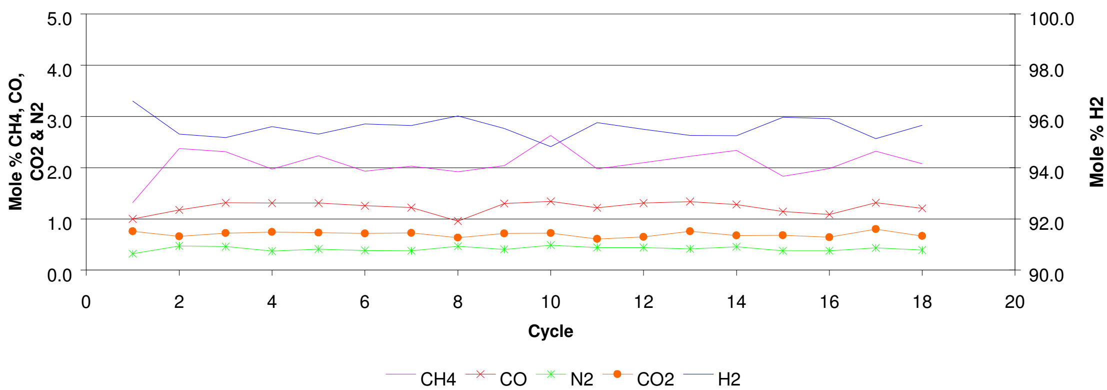
Average Reaction Efficiencies C2873-34-30/Crushed & C2873-19-31

Average Reaction Efficiencies
C2873-34-30/Crushed & C2873-19-31



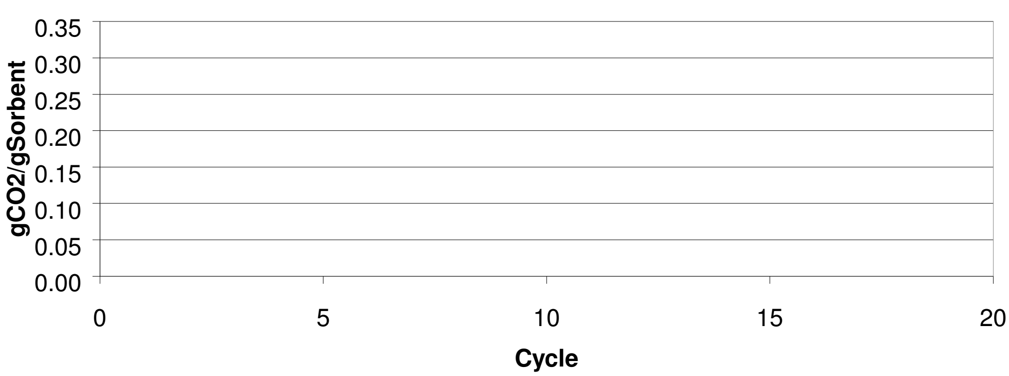
Average Reformate Composition C2873-34-30/Crushed & C2873-19-31

Average Reformate Composition
C2873-34-30/Crushed & C2873-19-31



gCO2 Sorbed per g Sorbent C2873-34-30/Crushed & C2873-19-31

gCO2 Sorbed per g Sorbent
C2873-34-30/Crushed & C2873-19-31



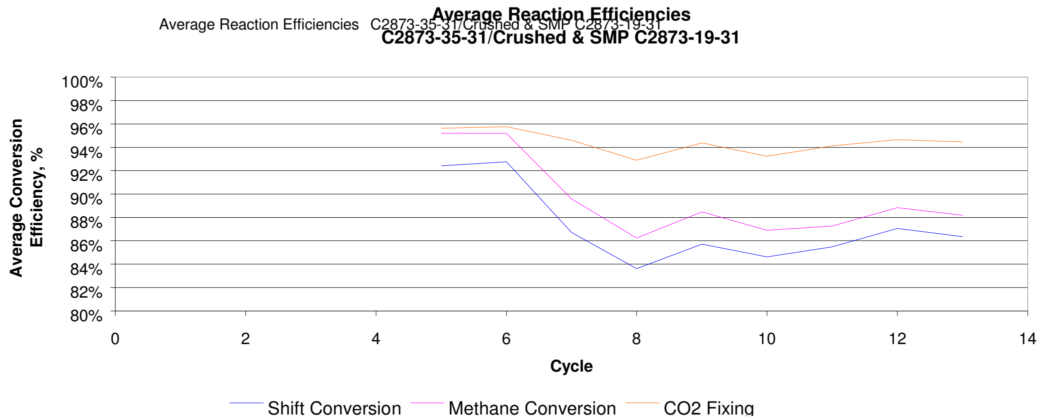
CO_2 Sorption Catalyst	C2873-35-31/Crushed
Reforming Catalyst: 0.5% rhodium o	SMP C2873-19-31
Composition CO_2 sorb	Ca Oxalate, 5wt% Al2O3
Binder	15% Al2O3
Batch No.	PCL178019C
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750C

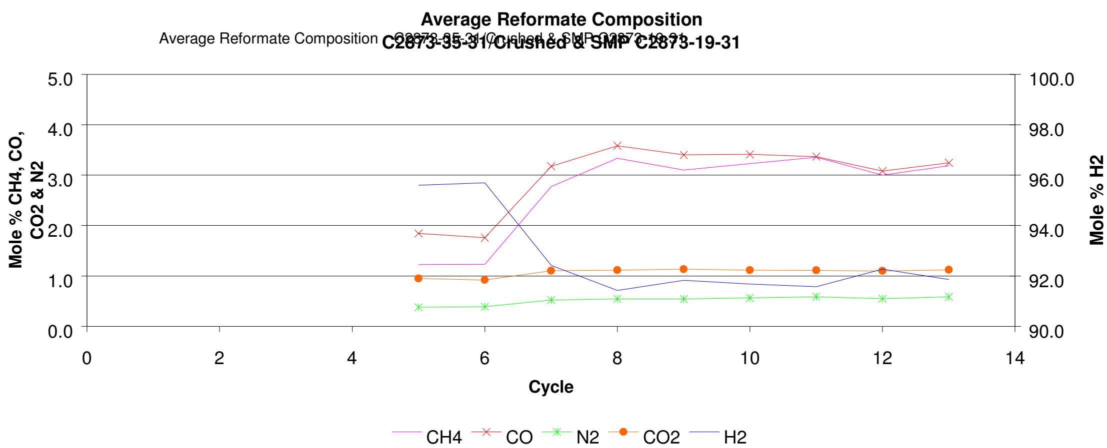
Wt. CO2 extrudate, g	19.52
Vol. CO2 extrudate, cc	22.4
Density CO2, g/cc	0.9
Wt. SMR Cat., g	3.98
Vol. SMR Cat., cc	4.6
Density SMR, g/cc	0.9
Total Bed Wt., g	23.50
Total Bed Vol., ml	26.9

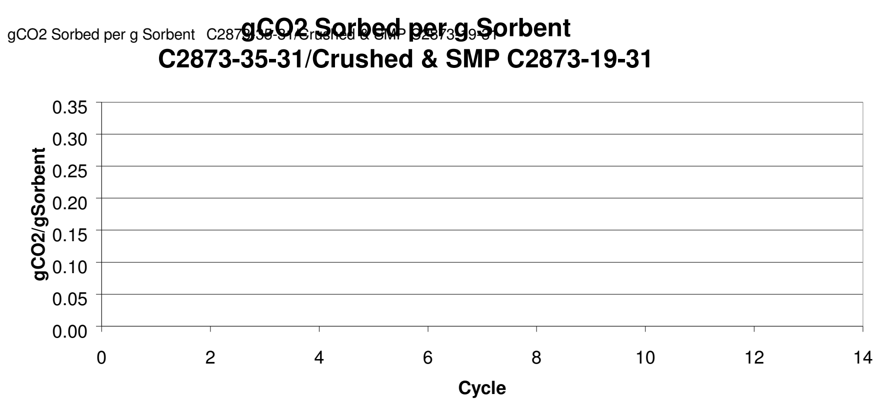
Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1												
2												
3												
4												
5	95.6	1.2	1.8	0.4	0.9	1496.92	92.4%	95.2%	95.6%	101.15	0.0037	0.38
6	95.7	1.2	1.8	0.4	0.9	1723.33	92.8%	95.2%	95.8%	99.62	0.0037	0.37
7	92.4	2.8	3.2	0.5	1.1	126.81	86.7%	89.6%	94.6%	92.84	0.0032	0.30
8	91.4	3.3	3.6	0.5	1.1	379.51	83.6%	86.3%	92.9%	90.97	0.0031	0.28
9	91.8	3.1	3.4	0.5	1.1	630.24	85.7%	88.5%	94.4%	88.11	0.0032	0.28
10	91.7	3.2	3.4	0.6	1.1	883.08	84.6%	86.9%	93.2%	87.38	0.0031	0.27
11	91.6	3.4	3.4	0.6	1.1	1133.39	85.5%	87.3%	94.1%	82.52	0.0031	0.26
12	92.3	3.0	3.1	0.5	1.1	1385.77	87.1%	88.8%	94.7%	79.46	0.0032	0.26
13	91.9	3.2	3.2	0.6	1.1	1639.12	86.4%	88.2%	94.5%	80.20	0.0032	0.25

Cycle 1 - 4: 200C Steam Soak


Average Reaction Efficiencies C2873-35-31/Crushed & SMP C2873-19-31
Average Reaction Efficiencies
C2873-35-31/Crushed & SMP C2873-19-31
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
2
4
6
8
10
12
14
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C2873-35-31/Crushed & SMP C2873-19-31
Average Reformate Composition
C2873-35-31/Crushed & SMP C2873-19-31
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0
2
4
6
8
10
12
14
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent C2873-35-31/Crushed & SMP C2873-19-31
gCO2 Sorbed per g Sorbent
C2873-35-31/Crushed & SMP C2873-19-31
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
14
Cycle

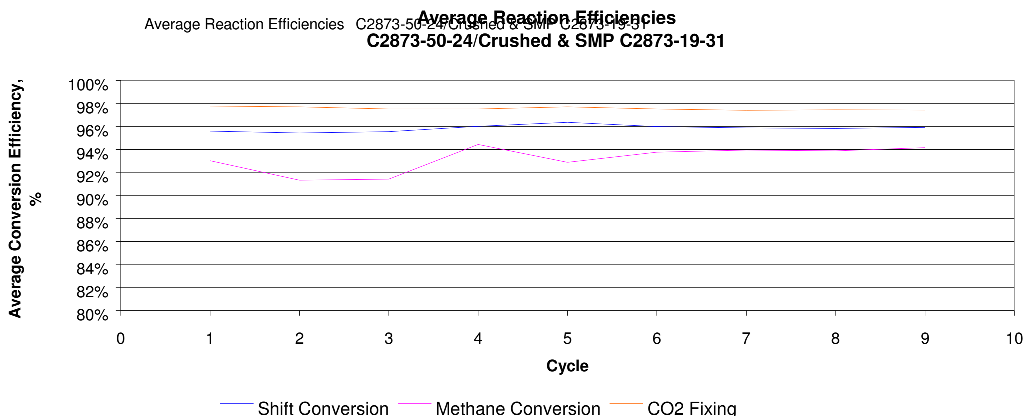
CO_2 Sorption Catalyst	C2873-50-24/Crushed
Reforming Catalyst: 0.5% rhodium or	SMP C2873-19-31
Composition CO_2 sorb	CaO/MgO (80:20)
Binder	15% Al2O3
Batch No.	HCM178157D
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750C

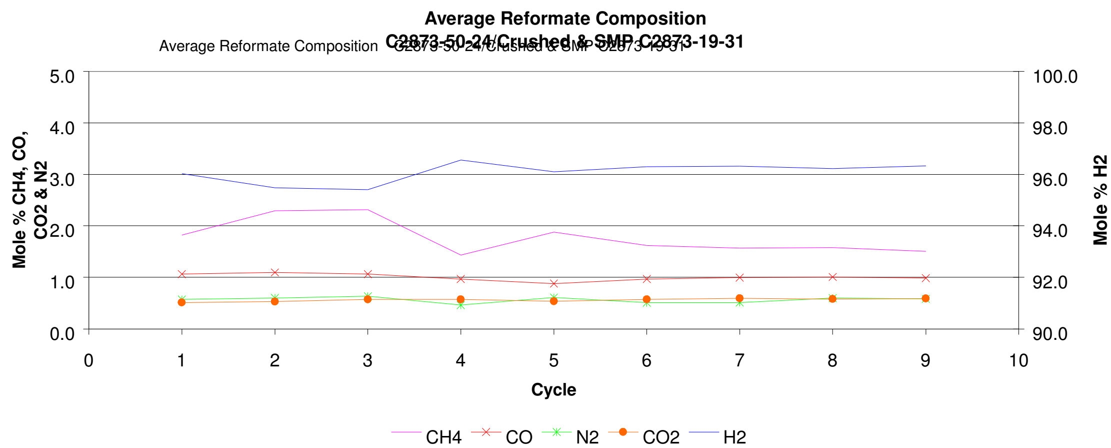
Wt. CO2 extrudate, g	19.56
Vol. CO2 extrudate, cc	34.1
Density CO2, g/cc	0.6
Wt. SMR Cat., g	3.93
Vol. SMR Cat., cc	6.8
Density SMR, g/cc	0.6
Total Bed Wt., g	23.49
Total Bed Vol., ml	40.9

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

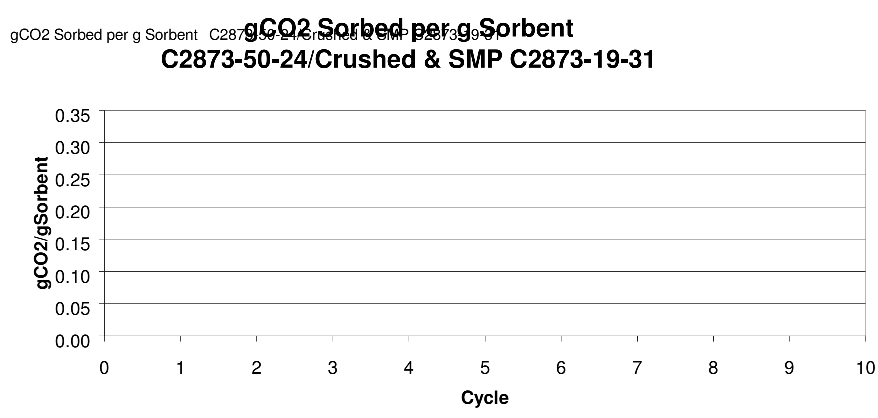
Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CE	Cycle Time	S	gCO2/gSorb
1	96.0	1.8	1.1	0.6	0.5	290.63	95.6%	93.0%	97.8%	39.92	0.0058	0.23
2	95.5	2.3	1.1	0.6	0.5	491.50	95.5%	91.3%	97.7%	38.01	0.0057	0.22
3	95.4	2.3	1.1	0.6	0.6	692.63	95.6%	91.4%	97.5%	36.84	0.0057	0.21
4	96.6	1.4	1.0	0.5	0.6	893.16	96.0%	94.5%	97.5%	34.41	0.0059	0.20
5	96.1	1.9	0.9	0.6	0.5	1093.98	96.4%	92.9%	97.7%	33.16	0.0058	0.19
6	96.3	1.6	1.0	0.5	0.6	1236.19	96.0%	93.8%	97.5%	30.29	0.0059	0.18
7	96.3	1.6	1.0	0.5	0.6	1376.46	95.9%	94.0%	97.4%	28.97	0.0059	0.17
8	96.2	1.6	1.0	0.6	0.6	1516.31	95.8%	93.9%	97.5%	28.19	0.0059	0.17
9	96.3	1.5	1.0	0.6	0.6	1656.79	95.9%	94.2%	97.4%	27.34	0.0059	0.16

Cycle 10 - 15 with 200C Steam





Missing 6 cycles (Stream Off)



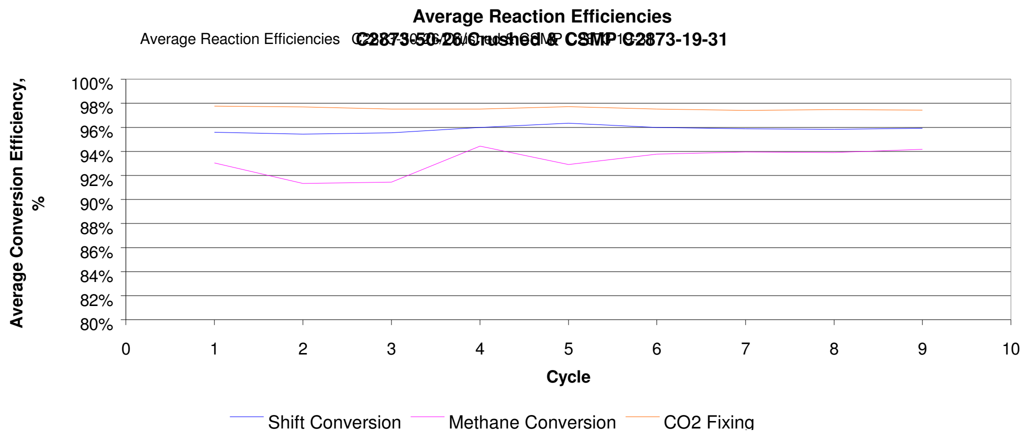
CO_2 Sorption Catalyst	C2873-50-26/Crushed
Reforming Catalyst: 0.5% rhodium or	CSMP C2873-19-31
Composition CO_2 sorb	CaO/MgO (80:20)
Binder	15% Al2O3
Batch No.	HCM178157D
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750C

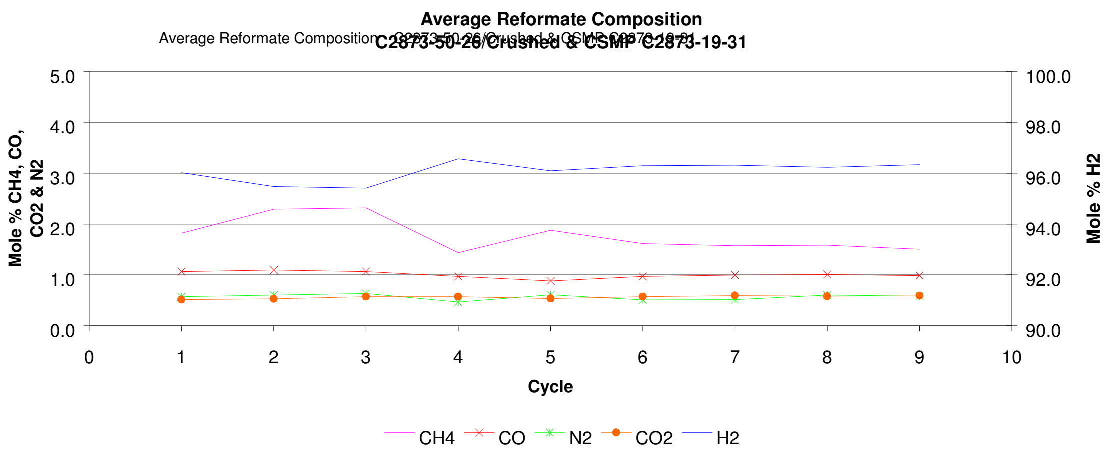
Wt. CO2 extrudate, g	19.55
Vol. CO2 extrudate, cc	35.0
Density CO2, g/cc	0.6
Wt. SMR Cat., g	3.93
Vol. SMR Cat., cc	7.0
Density SMR, g/cc	0.6
Total Bed Wt., g	23.48
Total Bed Vol., ml	42.0

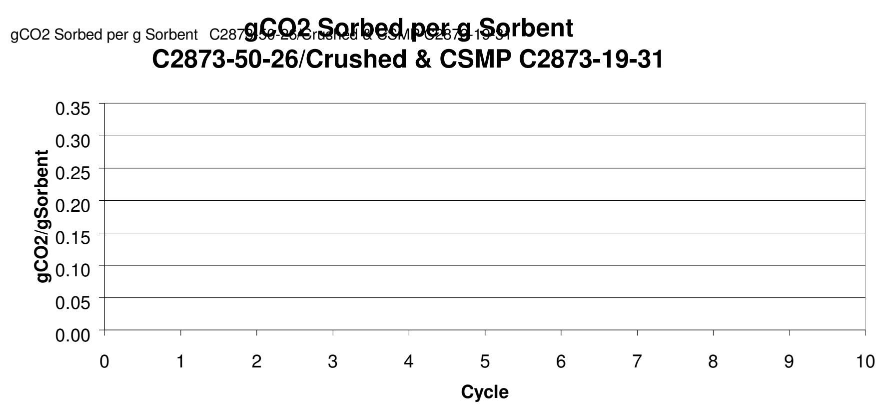
Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	96.0	1.8	1.1	0.6	0.5	290.63	95.6%	93.0%	97.8%	39.92	0.0058	0.23
2	95.5	2.3	1.1	0.6	0.5	491.50	95.5%	91.3%	97.7%	38.01	0.0057	0.22
3	95.4	2.3	1.1	0.6	0.6	692.63	95.6%	91.4%	97.5%	36.84	0.0057	0.21
4	96.6	1.4	1.0	0.5	0.6	893.16	96.0%	94.5%	97.5%	34.41	0.0059	0.20
5	96.1	1.9	0.9	0.6	0.5	1093.98	96.4%	92.9%	97.7%	33.16	0.0058	0.19
6	96.3	1.6	1.0	0.5	0.6	1236.19	96.0%	93.8%	97.5%	30.29	0.0059	0.18
7	96.3	1.6	1.0	0.5	0.6	1376.46	95.9%	94.0%	97.4%	28.97	0.0059	0.17
8	96.2	1.6	1.0	0.6	0.6	1516.31	95.8%	93.9%	97.5%	28.19	0.0059	0.17
9	96.3	1.5	1.0	0.6	0.6	1656.79	95.9%	94.2%	97.4%	27.34	0.0059	0.16

Cycle 10 - 15 with 200C Steam


Average Reaction Efficiencies
C2873-50-26/Crushed & CSMP C2873-19-31
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
1
2
3
4
5
6
7
8
9
10
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition
C2873-50-26/Crushed & CSMP C2873-19-31
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
1
2
3
4
5
6
7
8
9
10
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent
C2873-50-26/Crushed & CSMP C2873-19-31
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
7
8
9
10
Cycle

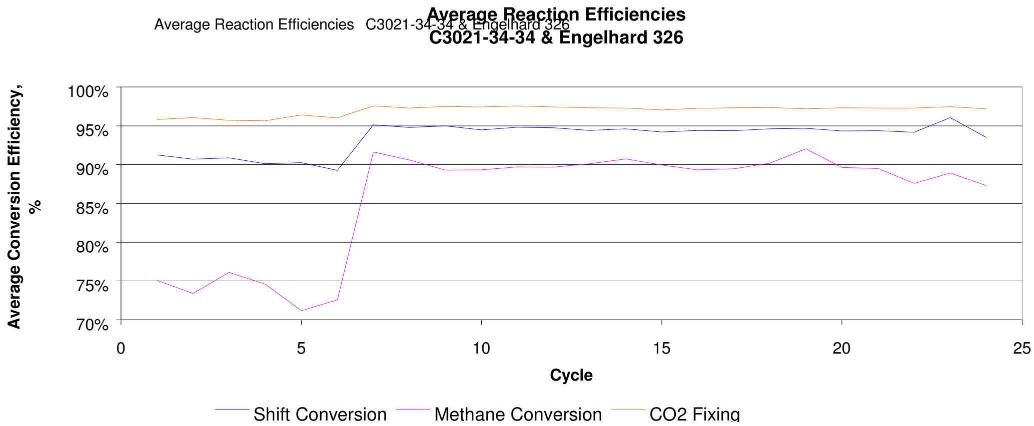
CO_2 Sorption Catalyst	C3021-34-34
Reforming Catalyst: 0.5% rhodium or	Engelhard 326
Composition CO_2 sorb	CaO/MgO (55:45)
Binder	15% Al2O3
Batch No.	HCM178165E
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	500C

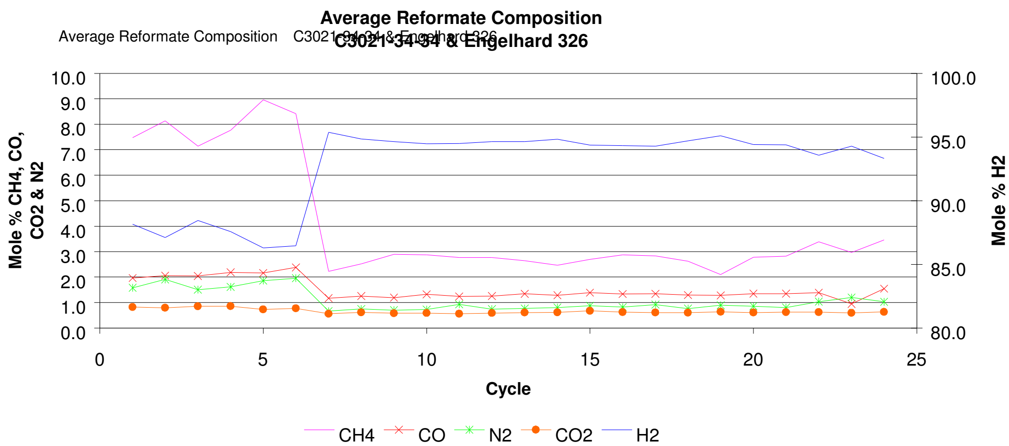
Wt. CO2 extrudate, g	25.01
Vol. CO2 extrudate, cc	33.7
Density CO2, g/cc	0.7
Wt. SMR Cat., g	5.00
Vol. SMR Cat., cc	9.0
Density SMR, g/cc	0.6
Total Bed Wt., g	30.01
Total Bed Vol., ml	42.7

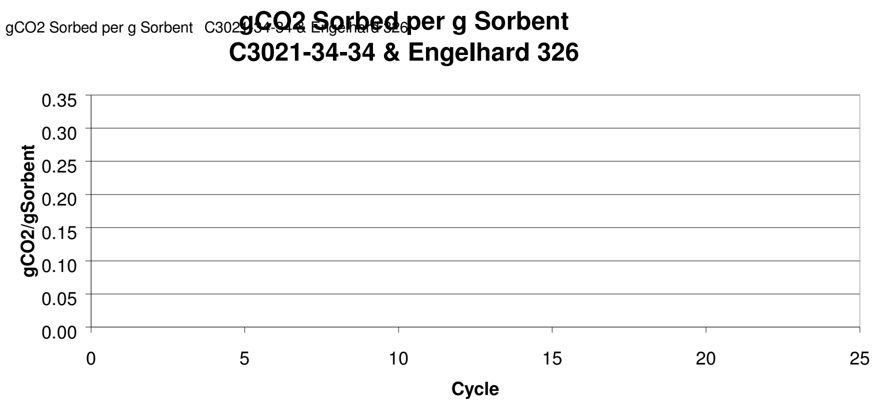
Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	88.1	7.5	2.0	1.6	0.8	193.93	91.2%	75.1%	95.8%	43.70		
2	87.1	8.1	2.1	1.9	0.8	382.95	90.7%	73.4%	96.1%	43.50		
3	88.4	7.1	2.0	1.5	0.8	572.34	90.9%	76.1%	95.7%	38.50		
4	87.6	7.8	2.2	1.6	0.9	761.92	90.1%	74.6%	95.6%	40.22		
5	86.3	9.0	2.2	1.9	0.7	951.87	90.2%	71.2%	96.4%	38.76		
6	86.5	8.4	2.4	2.0	0.8		89.3%	72.6%	96.0%	36.73		
7	95.4	2.2	1.2	0.7	0.6		95.1%	91.6%	97.6%	31.38	0.0043	0.13
8	94.8	2.5	1.3	0.8	0.6		94.8%	90.6%	97.3%	29.84	0.0042	0.13
9	94.6	2.9	1.2	0.7	0.6		95.0%	89.3%	97.5%	27.60	0.0042	0.12
10	94.5	2.9	1.3	0.7	0.6		94.5%	89.3%	97.4%	27.55	0.0041	0.11
11	94.5	2.8	1.2	0.9	0.6		94.8%	89.7%	97.5%	26.28	0.0042	0.11
12	94.6	2.8	1.3	0.7	0.6		94.7%	89.7%	97.4%	25.18	0.0042	0.11
13	94.6	2.6	1.3	0.8	0.6		94.4%	90.1%	97.3%	25.10	0.0042	0.10
14	94.8	2.5	1.3	0.8	0.6		94.6%	90.7%	97.3%	24.63	0.0042	0.10
15	94.4	2.7	1.4	0.9	0.7		94.2%	89.9%	97.0%	25.06	0.0041	0.10
16	94.3	2.9	1.3	0.8	0.6		94.4%	89.3%	97.2%	24.44	0.0041	0.10
17	94.3	2.8	1.3	0.9	0.6		94.4%	89.4%	97.3%	24.03	0.0041	0.10
18	94.7	2.6	1.3	0.8	0.6		94.6%	90.2%	97.4%	23.38	0.0042	0.10
19	95.1	2.1	1.3	0.9	0.6		94.7%	92.0%	97.2%	23.05	0.0043	0.10
20	94.4	2.8	1.3	0.9	0.6		94.3%	89.6%	97.3%	22.43	0.0042	0.09
21	94.4	2.8	1.3	0.8	0.6		94.3%	89.5%	97.3%	22.23	0.0041	0.09
22	93.6	3.4	1.4	1.0	0.6		94.2%	87.6%	97.3%	22.19	0.0040	0.09
23	94.3	3.0	0.9	1.2	0.6		96.0%	88.9%	97.5%	17.41	0.0042	0.07
24	93.3	3.5	1.5	1.0	0.6		93.5%	87.3%	97.2%	20.04	0.0040	0.08

Inlet 424 C; Outlet 601 C (Cycles 1-6)
Inlet 366 C; Outlet 601 C (Cycles 7-24)


Average Reaction Efficiencies C3021-34-34 & Engelhard 326
Average Reaction Efficiencies
C3021-34-34 & Engelhard 326
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
0
5
10
15
20
25
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C3021-34-34 & Engelhard 326
Average Reformate Composition
C3021-34-34 & Engelhard 326
Mole % CH4, CO, CO2 & N2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
95.0
90.0
85.0
80.0
0
5
10
15
20
25
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent C3021-34-34 & Engelhard 326
gCO2 Sorbed per g Sorbent
C3021-34-34 & Engelhard 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
Cycle

APPENDIX D

CO_2 Sorption Catalyst	CSMP 3021-28-29 IF	CSMP C3021-28-20 IF	CSMP C3021-28-22 IF	CSMP C3021-28-24 IF	CSMP C3021-28-31 IF	CSMP C3021-28-33 IF	CSMP C3021-28-35 IF
Reforming Catalyst	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)
Reactor	R1	R1	R2	R1	R2	R1	R2
Date loaded	6/4/2004	8/13/2004	8/13/2004	9/8/2004	9/8/2004	9/10/2004	9/10/2004
Date unloaded	6/14/2004		8/19/2004	9/10/2004	9/18/2004	9/16/2004	9/16/2004
Composition CO_2 sorb	90:10 wt/wt	90:10 wt/wt	90:10 wt/wt	90:10 wt/wt	90:10 wt/wt	90:10 wt/wt	90:10 wt/wt
(CaO/MgO)	(50:50CaO/MgO):(0.5wt%Rh/	(50:50CaO/MgO):(0.5wt%Rh/	(50:50CaO/MgO):(0.5wt%Rh/	(50:50CaO/MgO):(0.5wt%Rh/	(50:50CaO/MgO):(0.5wt%Rh/Al	(50:50CaO/MgO):(0.5wt%Rh/	(50:50CaO/MgO):(0.5wt%Rh/
Batch No.	HCl178144B	HCl178147C	HCl178148A	HCl178148B	HCl178144C	HCl178144D	HCl178144E
Extruded by	RTC	RTC	RTC	RTC	RTC	RTC	RTC
Powder Post Processed, °C	500	750	750	750	500	500	500
Calcined, °C	2 hrs @ 450°C	2 hrs @ 450°C	2 hrs @ 450°C	2 hrs @ 450°C	2 hrs @ 450°C	2 hrs @ 450°C	2 hrs @ 450°C
Tot wt. Of cat., g	29.5	29.4	36.28	34.69	27.3	26.61	31.61
Tot vol. Of cat., ml	40	40	40	40	40	40	40
Bulk density of cat., g/cc	0.7375	0.735	0.907	0.86725	0.6825	0.66525	0.79025
wt. CO_2 extrudate, g	25	24.9	31.78	30.19	22.8	22.11	27.11
wt. Rh extrudate, g	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Bulk density of Rh	0.6	0.6	0.6	0.6	0.6	0.6	0.6
GHSV, hr-1	390	390	390	390	390	390	390
Reforming, °C	600	600	600	600	600	600	600
Desorption, °C	800	800	800	800	800	800	800
Average Reformate Composition (Cycle 1)							
Average Mole % H_2	57.58	95.47	94.69	94.05	94.19	95.31	93.77
Average Mole % CH_4	31.02	1.45	1.65	1.89	2.51	1.49	3.10
Average Mole % CO	1.20	1.52	1.66	1.87	1.48	0.90	1.41
Average Mole % CO_2	9.45	0.67	0.78	0.53	0.45	1.17	0.62
Average Mole % N2	0.73	0.87	1.21	1.64	1.33	1.09	1.08
Conversion Efficiencies C							
Shift Conversion (WGS)	0.91	0.94	0.93	0.92	0.94	0.96	0.94
CH_4 Conversion (CC)	0.36	0.94	0.94	0.93	0.91	0.94	0.88
CO_2 Sorption or Fixing (CF)	0.95	0.96	0.95	0.93	0.94	0.95	0.95
Catalyst Extrudate Shape							
Average Reformate Comp							
Average Mole % H_2		95.44	94.68			95.07	95.07
Average Mole % CH_4		1.44	1.81			1.92	2.23
Average Mole % CO		1.39	1.53			1.14	1.16
Average Mole % CO_2		0.81	0.88			0.66	0.50
Average Mole % N2		0.90	1.08			1.18	1.00
Conversion Efficiencies Calculated from Average Ref							
Shift Conversion (WGS)		0.94	0.94			0.95	0.95
CH_4 Conversion (CC)		0.94	0.93			0.93	0.92
CO_2 Sorption or Fixing (CF)		0.96	0.95			0.95	0.96
Catalyst Extrudate Shape							

CO_2 Sorption Catalyst Reforming Catalyst	CSMP 2873-29-36 IF CSMP 2873-29-36 IF	CSMP C3021-28-16 IF CSMP C3021-28-16 IF	CSMP C3021-28-18 IF CSMP C3021-28-16 IF	CSMP C3021-28-20 IF Engelhard Escat 326 (0.5%Rh on Alumina)	CSMP C3021-28-22 IF Engelhard Escat 326 (0.5%Rh on Alumina)	CSMP C3021-28-24 IF Engelhard Escat 326 (0.5%Rh on Alumina)
Composition CO_2 sorb CaO/MgO		90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/ Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/ Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/ Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/ Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/ Al2O3)
Batch No.		HCl178147A	HCl178147B	HCl178147C	HCl178148A	HCl178148B
Extruded by	RTC	RTC	RTC	RTC	RTC	RTC
Powder Post Processed, °C				750	750	750
Calcined, °C				2 hrs @ 450°C	2 hrs @ 450°C	2 hrs @ 450°C
wt. CO_2 extrudate, g	18.24	18.26	23.76	24.9	31.78	30.19
Vol. CO2 extrudate, cc	20.0	20.0	25.0	32.5	32.5	32.5
Density CO2, g/cc	0.9	0.9	1.0	0.8	1.0	0.9
Wt. SMR Cat., g	0	0	0	4.5	4.5	4.5
Vol. SMR Cat., cc		0.0	0.0	7.5	7.5	7.5
Density SMR, g/cc				0.6	0.6	0.6
Total Bed wt., g	18.24	18.26	23.76	29.4	36.28	34.69
Total Bed Vol., ml	20.0	20.0	25.0	40.0	40.0	40.0
Reactor	R1	R2	R1	R1	R2	R1
S/C	3	3	3	3	3	3
GHSV, hr-1	390	390	390	390	390	390
Reforming, °C	600	600	600	600	600	600
Calcination, °C	755	755	755	800	800	800
Pressure, atm	1	1	1	1	1	1
Date loaded	12/16/2003	12/16/2003	1/22/2004	8/13/2004	8/13/2004	9/8/2004
Date unloaded	12/17/2003	12/17/2003	1/23/2004		8/19/2004	9/10/2004
Sample	Crushed	Crushed	Crushed			
		DID NOT PRODUCE OVER 25% H2	DID NOT PRODUCE OVER 67% H2			
Post Run Description					**No powder**	**No powder**
Size					**Normal size**	**Normal size**
Discoloration					**Slight discoloration**	**Slight discoloration**

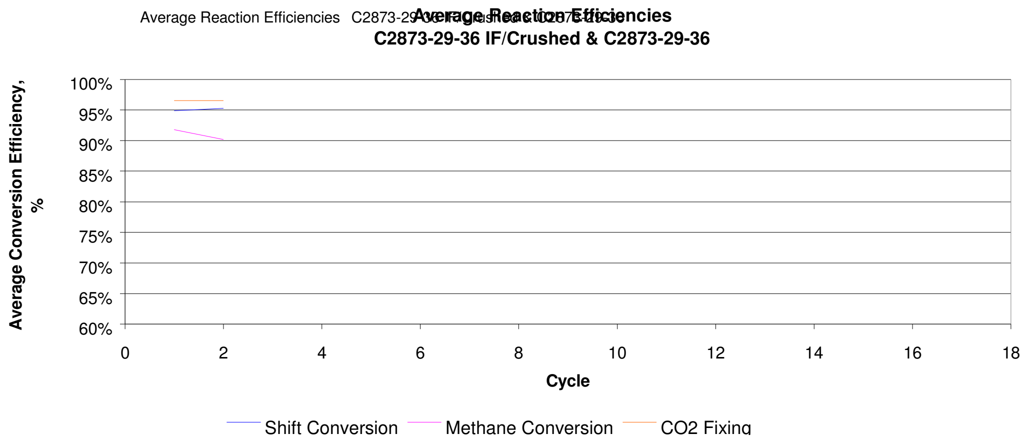
CO_2 Sorption Catalyst Reforming Catalyst	CSMP C3021-28-27 IF CSMP C3021-28-27 IF	CSMP C3021-28-29 IF CSMP C3021-28-29 IF	CSMP 3021-28-29 IF Engelhard Escat 326 (0.5%Rh on Alumina)	CSMP C3021-28-31 IF Engelhard Escat 326 (0.5%Rh on Alumina)	CSMP C3021-28-33 IF Engelhard Escat 326 (0.5%Rh on Alumina)	CSMP C3021-28-35 IF Engelhard Escat 326 (0.5%Rh on Alumina)
Composition CO_2 sorb CaO/MgO	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/Al2O3)	90:10 wt/wt (50:50CaO/MgO):(0.5wt%Rh/Al2O3)
Batch No.	HCl178144A	HCl178144B	HCl178144B	HCl178144C	HCl178144D	HCl178144E
Extruded by	RTC	RTC	RTC	RTC	RTC	RTC
Powder Post Processed, °C			500	500	500	500
Calcined, °C			2 hrs @ 450°C	2 hrs @ 450°C	2 hrs @ 450°C	2 hrs @ 450°C
wt. CO_2 extrudate, g	23.93	25.27	25	22.8	22.11	27.11
Vol. CO2 extrudate, cc	35.0	35.0	32.5	32.5	32.5	32.5
Density CO2, g/cc	0.7	0.7	0.8	0.7	0.7	0.8
Wt. SMR Cat., g	0	0	4.5	4.5	4.5	4.5
Vol. SMR Cat., cc	0.0	0.0	7.5	7.5	7.5	7.5
Density SMR, g/cc			0.6	0.6	0.6	0.6
Total Bed wt., g	23.93	25.27	29.5	27.3	26.61	31.61
Total Bed Vol., ml	35.0	35.0	40.0	40.0	40.0	40.0
Reactor	R1	R1	R1	R2	R1	R2
S/C	3	3	3	3	3	3
GHSV, hr-1	390	390	390	390	390	390
Reforming, °C	600	600	600	600	600	600
Calcination, °C	755	755	800	800	800	800
Pressure, atm	1	1	1	1	1	1
Date loaded	1/7/2004	2/2/2004	6/4/2004	9/8/2004	9/10/2004	9/10/2004
Date unloaded	1/8/2004	2/3/2004	6/14/2004	9/18/2004	9/16/2004	9/16/2004
Sample	Crushed	Crushed				
	DID NOT PRODUCE OVER 67% H2	DID NOT PRODUCE OVER 71% H2				
Post Run Description			**40% powder**	**No powder**	**No powder**	**Some powder**
Size			**30% normal extrudates**	**Extrudates normal size**	**Normal size**	**Normal extrudate**
Discoloration			**30% damaged**	**Slight discoloration**		**Slight discoloration**

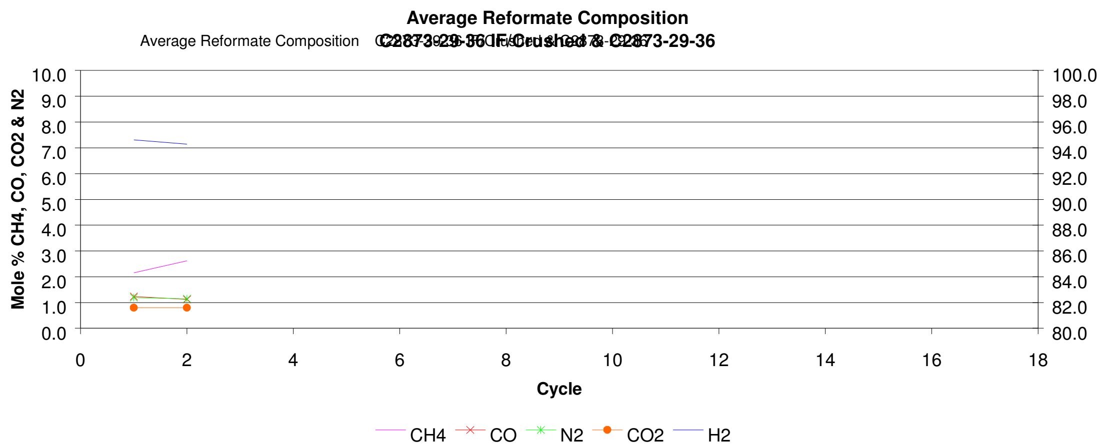
CO_2 Sorption Catalyst	C2873-29-36 IF/Crushed
Reforming Catalyst: 0.5% rhodium or	C2873-29-36
Composition CO_2 sorb	
Binder	
Batch No.	
Extruded by	RTC
Powder Post Processed	
Calcined, C	

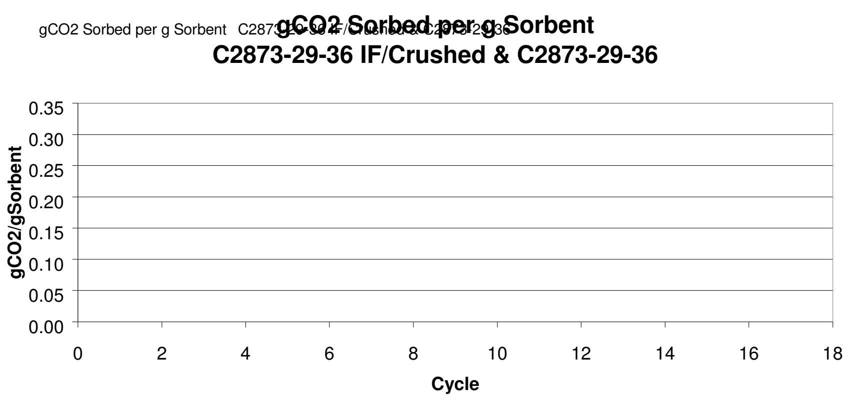
Wt. CO2 extrudate, g	18.24
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.6
SMR Cat. Wt., g	
SMR Cat. Vol, cc	
Density SMR, g/cc	
Total Bed wt., g	18.24
Total Bed Vol., ml	32.5

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	755
Pressure, atm	1

	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	94.6	2.1	1.2	1.2	0.8	172.13	94.8%	91.8%	96.5%	18.92	0.0046	0.09
2	94.3	2.6	1.1	1.1	0.8	319.26	95.3%	90.2%	96.5%	18.02	0.0045	0.08


Average Reaction Efficiencies   C2873-29-36 IF/Crushed & C2873-29-36
Average Reaction Efficiencies
C2873-29-36 IF/Crushed & C2873-29-36
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
65%
60%
0
2
4
6
8
10
12
14
16
18
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition
C2873-29-36 IF/Crushed & C2873-29-36
Average Reformate Composition   C2873-29-36 IF/Crushed & C2873-29-36
Mole % CH4, CO, CO2 & N2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
88.0
86.0
84.0
82.0
80.0
0
2
4
6
8
10
12
14
16
18
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent   C2873-29-36 IF/Crushed & C2873-29-36
gCO2 Sorbed per g Sorbent
C2873-29-36 IF/Crushed & C2873-29-36
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
14
16
18
Cycle

CO_2 Sorption Catalyst	C3021-28-16 IF
Reforming Catalyst: 0.5% rhodium on	C3021-28-16 IF
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3	
Batch No.	HCl178147A
Extruded by	RTC
Oven Atmosphere	
Calcined, C	

wt. CO2 extrudate, g	18.26
Vol. CO2 extrudate, cc	20.0
Density CO2, g/cc	0.9
SMR Cat. Wt., g	
SMR Cat. Vol, cc	
Density SMR, g/cc	
Total Bed wt., g	18.26
Total Bed Vol., ml	20.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	755
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	No cycle with H2>90%											
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												

CO_2 Sorption Catalyst	C3021-28-18 IF
Reforming Catalyst: 0.5% rhodium or	C3021-28-16 IF
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3)	
Batch No.	HCl178147B
Extruded by	RTC
Oven Atmosphere	
Calcined, C	

wt. CO2 extrudate, g	19.53
Vol. CO2 extrudate, cc	32.6
Density CO2, g/cc	0.6
SMR Cat. Wt., g	3.91
SMR Cat. Vol, cc	6.5
Density SMR, g/cc	0.6
Total Bed wt., g	23.44
Total Bed Vol., ml	39.1

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	750
Pressure, atm	1

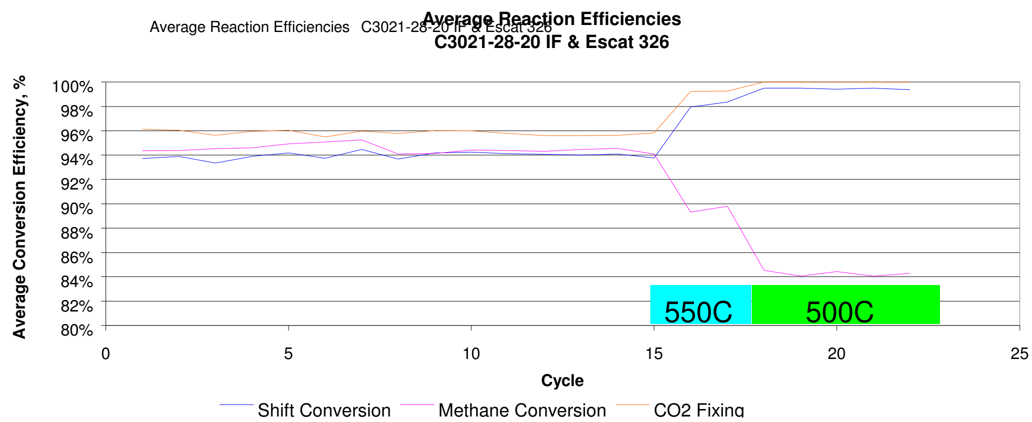
Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	57.6	31.0	1.2	9.4	0.7	209.53	91.1%	36.1%	94.9%			
2	50.8	32.6	1.1	14.8	0.6	356.33	91.0%	30.0%	95.5%			
3	45.9	30.5	0.9	22.1	0.5	554.41	91.8%	29.6%	96.2%			
4	42.0	31.6	0.9	25.1	0.4	703.91	91.7%	25.7%	96.4%			
5	42.8	32.6	0.9	23.3	0.5	853.84	92.1%	25.7%	96.3%			
6	42.2	32.1	0.9	24.4	0.4	887.18	91.9%	25.6%	96.2%			
7	40.4	30.9	0.9	27.3	0.4	1153.74	91.1%	25.2%	96.3%			
8	40.6	31.8	0.8	26.3	0.4	1303.51	92.2%	24.6%	96.5%			
9	66.5	19.4	0.5	10.0	1.0	1325.33	96.8%	50.9%	94.6%			

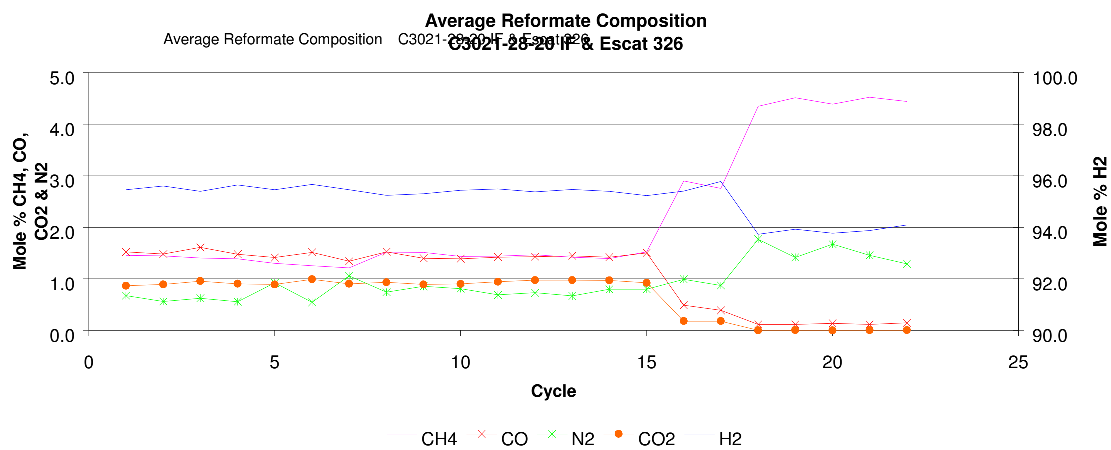
CO_2 Sorption Catalyst	C3021-28-20 IF
Reforming Catalyst: 0.5% rhodium o	Escat 326
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3)	
Batch No.	HCI178147C
Extruded by	RTC
Powder Post Processed	750.0
Calcined, C	2 hrs @ 450°C

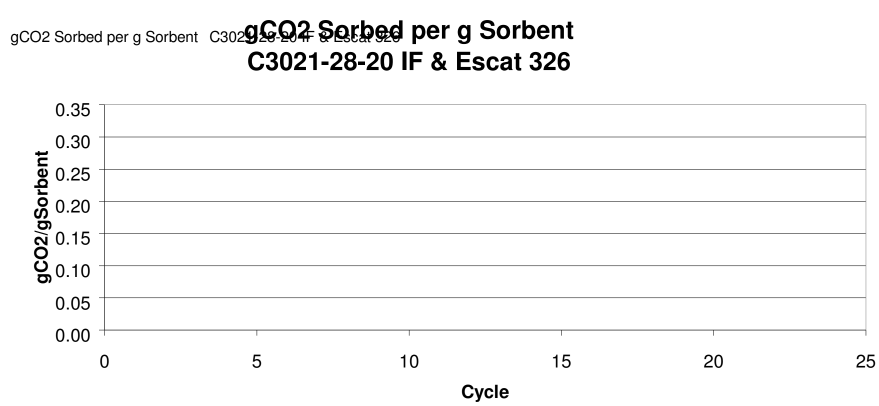
Wt. CO2 extrudate, g	24.90
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
SMR Cat. Wt., g	4.50
SMR Cat. Vol, cc	7.5
Density SMR, g/cc	0.6
Total Bed wt., g	29.40
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CE	Cycle Time	S	gCO2/gSorb	
1	95.5	1.5	1.5	0.7	0.9	198.09	93.7%	94.3%	96.1%	21.08	0.0044	0.09	
2	95.6	1.4	1.5	0.6	0.9	377.23	93.9%	94.4%	96.0%	19.59	0.0044	0.09	
3	95.4	1.4	1.6	0.6	1.0	557.31	93.3%	94.5%	95.6%	19.54	0.0043	0.08	
4	95.6	1.4	1.5	0.6	0.9	736.68	93.9%	94.6%	96.0%	18.11	0.0044	0.08	
5	95.5	1.3	1.4	0.9	0.9	915.86	94.2%	94.9%	96.0%	18.12	0.0044	0.08	
6	95.7	1.3	1.5	0.5	1.0	1096.07	93.7%	95.1%	95.5%	18.10	0.0044	0.08	
7	95.5	1.2	1.3	1.1	0.9	1275.42	94.5%	95.2%	96.0%	18.07	0.0044	0.08	
8	95.2	1.5	1.5	0.7	0.9	1456.49	93.7%	94.1%	95.8%	16.67	0.0043	0.07	
9	95.3	1.5	1.4	0.9	0.9	1635.75	94.2%	94.1%	96.0%	16.86	0.0044	0.07	
10	95.4	1.4	1.4	0.8	0.9	1995.35	94.2%	94.4%	96.0%	17.14	0.0044	0.08	
11	95.5	1.4	1.4	0.7	0.9	2175.95	94.1%	94.4%	95.8%	16.82	0.0044	0.07	
12	95.4	1.5	1.4	0.7	1.0	2355.59	94.1%	94.3%	95.6%	17.61	0.0044	0.08	
13	95.5	1.4	1.4	0.7	1.0	2535.84	94.0%	94.5%	95.6%	16.69	0.0044	0.07	
14	95.4	1.4	1.4	0.8	1.0	2715.32	94.1%	94.6%	95.6%	17.58	0.0044	0.08	Reforming
15	95.2	1.5	1.5	0.8	0.9	2895.81	93.8%	94.1%	95.8%	17.41	0.0043	0.08	550C
16	95.4	2.9	0.5	1.0	0.2	3076.38	97.9%	89.3%	99.2%	14.54	0.0045	0.06	550C
17	95.8	2.8	0.4	0.9	0.2	3255.56	98.4%	89.8%	99.3%	13.62	0.0045	0.06	550C
18	93.7	4.4	0.1	1.8	0.0	3439.86	99.5%	84.5%	100.0%	11.23	0.0043	0.05	500C
19	93.9	4.5	0.1	1.4	0.0	3619.59	99.5%	84.1%	100.0%	10.13	0.0043	0.04	500C
20	93.8	4.4	0.1	1.7	0.0	3799.02	99.4%	84.4%	100.0%	9.04	0.0043	0.04	500C
21	93.9	4.5	0.1	1.5	0.0	3996.73	99.5%	84.1%	100.0%	8.98	0.0043	0.04	500C
22	94.1	4.4	0.1	1.3	0.0	4158.77	99.4%	84.3%	100.0%	7.85	0.0043	0.03	500C


Average Reaction Efficiencies C3021-28-20 IF & Escat 326
Average Reaction Efficiencies
C3021-28-20 IF & Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
550C
500C
0
5
10
15
20
25
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C3021-28-20 IF & Escat 326
Average Reformate Composition
C3021-28-20 IF & Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0
5
10
15
20
25
Cycle
CH4
CO
N2
CO2
H2

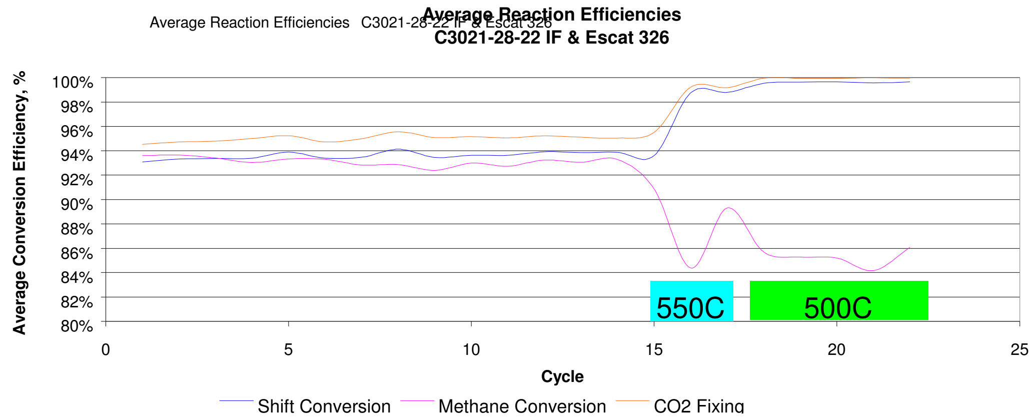

gCO2 Sorbed per g Sorbent C3021-28-20 IF & Escat 326
gCO2 Sorbed per g Sorbent
C3021-28-20 IF & Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
Cycle

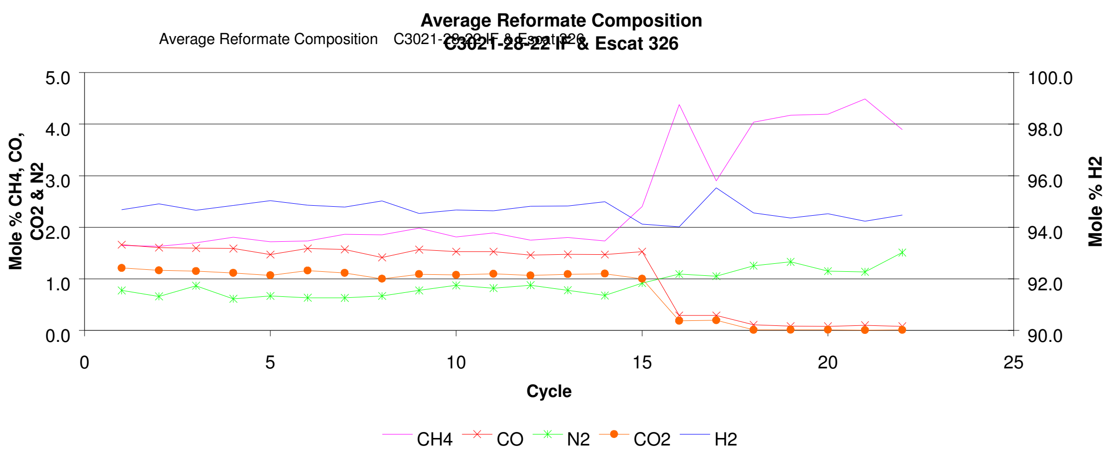
CO_2 Sorption Catalyst	C3021-28-22 IF
Reforming Catalyst: 0.5% rhodium o	Escat 326
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3)	
Batch No.	HCl178148A
Extruded by	RTC
Powder Post Processed	750.0
Calcined, C	2 hrs @ 450°C

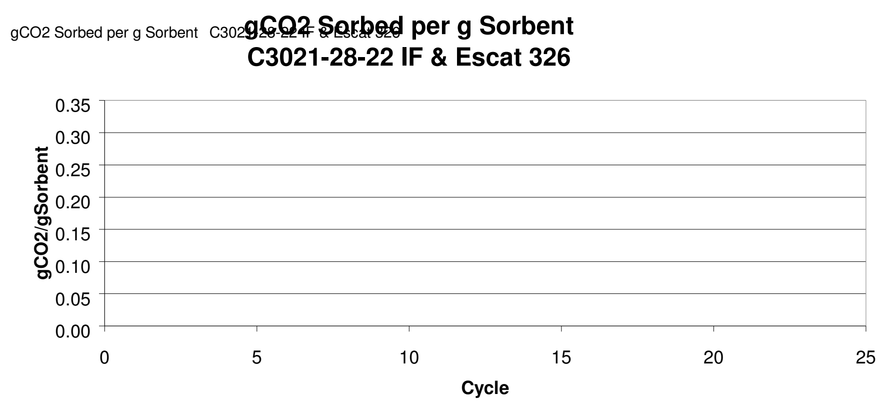
Wt. CO2 extrudate, g	31.78
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	1.0
SMR Cat. Wt., g	4.50
SMR Cat. Vol, cc	7.5
Density SMR, g/cc	0.6
Total Bed wt., g	36.28
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CE	Cycle Time	S	gCO2/gSorb	
1	94.7	1.6	1.7	0.8	1.2	201.85	93.1%	93.6%	94.5%	31.43	0.0033	0.10	
2	94.9	1.6	1.6	0.7	1.2	381.77	93.3%	93.7%	94.7%	28.55	0.0033	0.10	
3	94.7	1.7	1.6	0.9	1.2	560.33	93.4%	93.4%	94.8%	28.47	0.0033	0.09	
4	94.9	1.8	1.6	0.6	1.1	740.46	93.4%	93.0%	95.0%	25.52	0.0033	0.08	
5	95.0	1.7	1.5	0.7	1.1	919.66	93.9%	93.3%	95.2%	25.56	0.0034	0.09	
6	94.9	1.7	1.6	0.6	1.2	1100.12	93.4%	93.3%	94.7%	25.57	0.0033	0.08	
7	94.8	1.9	1.6	0.6	1.1	1279.98	93.5%	92.8%	95.0%	24.10	0.0033	0.08	
8	95.0	1.9	1.4	0.7	1.0	1459.33	94.1%	92.9%	95.6%	22.20	0.0034	0.07	
9	94.5	2.0	1.6	0.8	1.1	1738.07	93.5%	92.4%	95.1%	23.76	0.0033	0.08	
10	94.7	1.8	1.5	0.9	1.1	1998.78	93.6%	93.0%	95.2%	23.87	0.0033	0.08	
11	94.6	1.9	1.5	0.8	1.1	2178.65	93.6%	92.7%	95.1%	24.29	0.0033	0.08	
12	94.8	1.8	1.5	0.9	1.1	2358.28	93.9%	93.2%	95.2%	23.54	0.0034	0.08	
13	94.8	1.8	1.5	0.8	1.1	2538.15	93.9%	93.1%	95.1%	23.38	0.0033	0.08	
14	95.0	1.7	1.5	0.7	1.1	2718.40	93.9%	93.3%	95.0%	22.81	0.0033	0.08	Reforming
15	94.1	2.4	1.5	0.9	1.0	2898.48	93.6%	90.9%	95.5%	21.88	0.0033	0.07	550C
16	94.0	4.4	0.3	1.1	0.2	3079.75	98.8%	84.4%	99.2%	21.22	0.0033	0.07	550C
17	95.5	2.9	0.3	1.1	0.2	3258.99	98.8%	89.3%	99.2%	20.22	0.0035	0.07	550C
18	94.6	4.0	0.1	1.3	0.0	3443.27	99.5%	85.7%	100.0%	18.07	0.0034	0.06	500C
19	94.4	4.2	0.1	1.3	0.0	3623.00	99.6%	85.3%	99.9%	16.87	0.0034	0.06	500C
20	94.5	4.2	0.1	1.1	0.0	3802.44	99.7%	85.2%	99.9%	15.77	0.0034	0.05	500C
21	94.2	4.5	0.1	1.1	0.0	3982.56	99.6%	84.2%	100.0%	13.56	0.0034	0.05	500C
22	94.5	3.9	0.1	1.5	0.0	4161.04	99.7%	86.1%	100.0%	14.65	0.0034	0.05	500C


Average Reaction Efficiencies C3021-28-22 IF & Escat 326
Average Reaction Efficiencies
C3021-28-22 IF & Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
5
10
15
20
25
Cycle
550C
500C
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C3021-28-22 IF & Escat 326
Average Reformate Composition
C3021-28-22 IF & Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
5
10
15
20
25
Cycle
CH4
CO
N2
CO2
H2

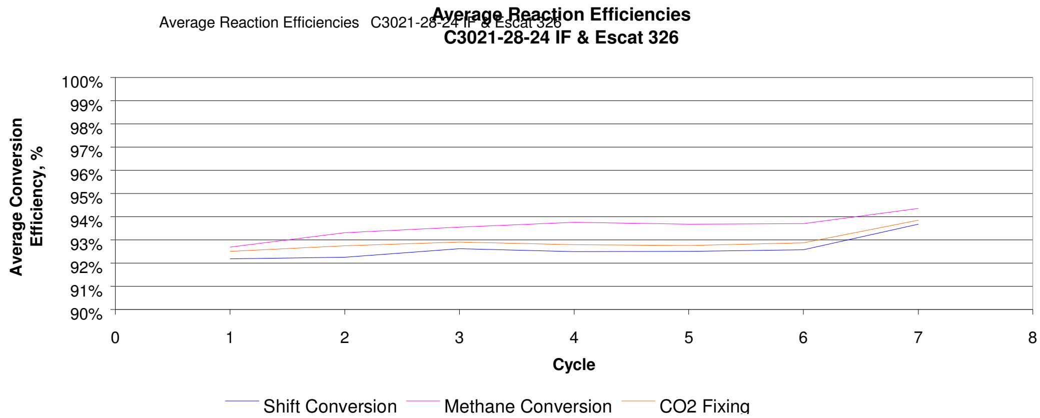

gCO2 Sorbed per g Sorbent C3021-28-22 IF & Escat 326
gCO2 Sorbed per g Sorbent
C3021-28-22 IF & Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
Cycle

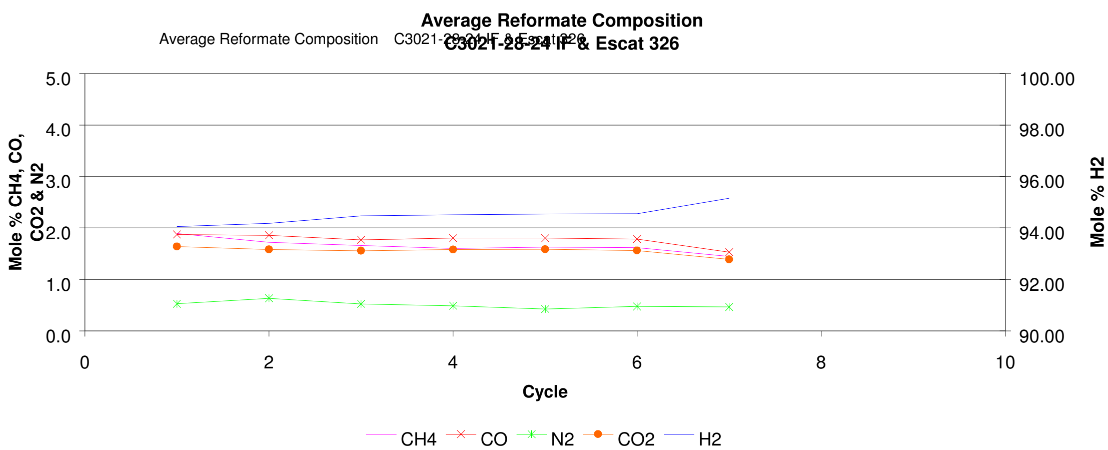
CO_2 Sorption Catalyst	C3021-28-24 IF
Reforming Catalyst: 0.5% rhodium or	Escat 326
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3)	
Batch No.	HCl178148B
Extruded by	RTC
Powder Post Processed	750.0
Calcined, C	2 hrs @ 450°C

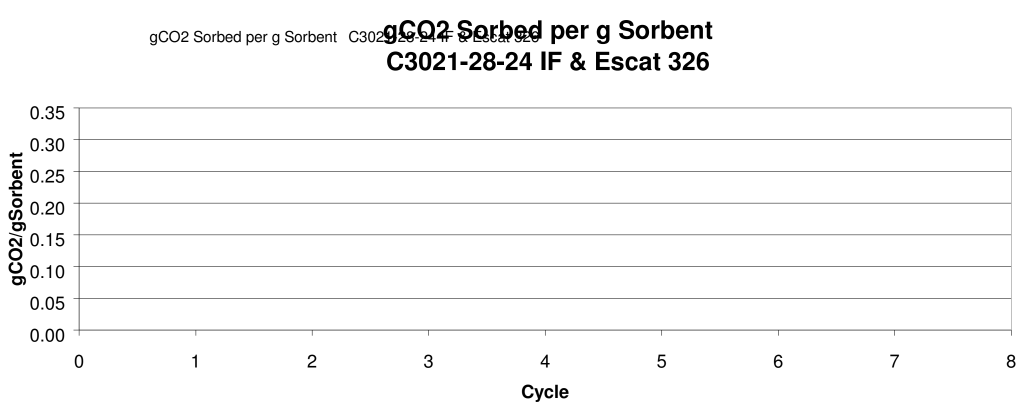
Wt. CO2 extrudate, g	30.19
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.9
SMR Cat. Wt., g	4.50
SMR Cat. Vol, cc	7.5
Density SMR, g/cc	0.6
Total Bed wt., g	34.69
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	94.05	1.89	1.87	0.53	1.64	210.72	92.18%	92.69%	92.51%	24.49	0.0037	0.09
2	94.18	1.72	1.86	0.63	1.58	390.26	92.25%	93.32%	92.74%	23.16	0.0038	0.09
3	94.48	1.66	1.77	0.52	1.56	569.60	92.63%	93.55%	92.91%	22.33	0.0038	0.09
4	94.51	1.60	1.80	0.49	1.58	749.77	92.50%	93.77%	92.79%	21.65	0.0038	0.08
5	94.55	1.63	1.80	0.42	1.59	929.52	92.51%	93.68%	92.76%	21.60	0.0038	0.08
6	94.55	1.62	1.78	0.47	1.56	1109.56	92.58%	93.71%	92.88%	20.87	0.0038	0.08
7	95.16	1.45	1.53	0.46	1.39	1287.33	93.68%	94.35%	93.85%	17.20	0.0039	0.07


Average Reaction Efficiencies C3021-28-24 IF & Escat 326
Average Reaction Efficiencies
C3021-28-24 IF & Escat 326
Average Conversion Efficiency, %
100%
99%
98%
97%
96%
95%
94%
93%
92%
91%
90%
0
1
2
3
4
5
6
7
8
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C3021-28-24 IF & Escat 326
Average Reformate Composition
C3021-28-24 IF & Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
100.00
98.00
96.00
94.00
92.00
90.00
Mole % H2
0
2
4
6
8
10
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent C3021-28-24 IF & Escat 326
gCO2 Sorbed per g Sorbent
C3021-28-24 IF & Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
7
8
Cycle

CO_2 Sorption Catalyst	CSMP C3021-28-27 IF
Reforming Catalyst: 0.5% rhodium or	CSMP C3021-28-27 IF
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3)	
Batch No.	HCl178144A
Extruded by	RTC
Oven Atmosphere	
Calcined, C	

wt. CO2 extrudate, g	23.93
Vol. CO2 extrudate, cc	35.0
Density CO2, g/cc	0.7
SMR Cat. Wt., g	
SMR Cat. Vol, cc	
Density SMR, g/cc	
Total Bed wt., g	23.93
Total Bed Vol., ml	35.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	755
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	αCO2 / αSorb
1	57.6	31.0	1.2	9.4	0.7	209.53	91.1%	36.1%	94.9%	16.86		
2	50.8	32.6	1.1	14.8	0.6	356.33	91.0%	30.0%	95.5%	7.30		
3	45.9	30.5	0.9	22.1	0.5	554.41	91.8%	29.6%	96.2%	8.56		
4	42.0	31.6	0.9	25.1	0.4	703.91	91.7%	25.7%	96.4%	2.76		
5	42.8	32.6	0.9	23.3	0.5	853.84	92.1%	25.7%	96.3%	3.58		
6	42.2	32.1	0.9	24.4	0.4	887.18	91.9%	25.6%	96.2%	0.80		
7	40.4	30.9	0.9	27.3	0.4	1153.74	91.1%	25.2%	96.3%	1.39		
8	40.6	31.8	0.8	26.3	0.4	1303.51	92.2%	24.6%	96.5%	0.70		
9	66.5	19.4	0.5	10.0	1.0	1325.33	96.8%	50.9%	94.6%	0.68		

CO_2 Sorption Catalyst	CSMP C3021-28-29 IF
Reforming Catalyst: 0.5% rhodium or	CSMP C3021-28-29 IF
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3)	
Batch No.	HCl178144B
Extruded by	RTC
Oven Atmosphere	
Calcined, C	

wt. CO2 extrudate, g	25.27
Vol. CO2 extrudate, cc	35.0
Density CO2, g/cc	0.7
SMR Cat. Wt., g	
SMR Cat. Vol, cc	
Density SMR, g/cc	
Total Bed wt., g	25.27
Total Bed Vol., ml	35.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	755
Pressure, atm	1

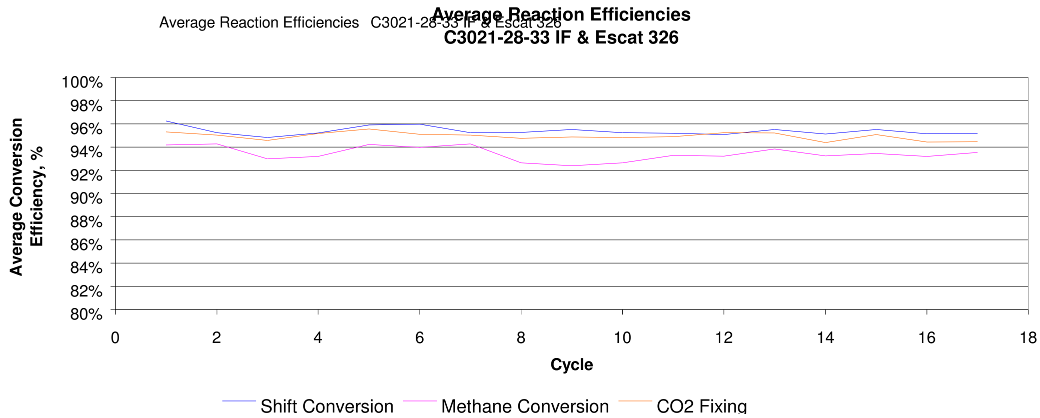
Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	57.6	31.0	1.2	9.4	0.7	209.53	91.1%	36.1%	94.9%	16.86	0.0015	0.03
2	50.8	32.6	1.1	14.8	0.6	356.33	91.0%	30.0%	95.5%	7.30	0.0012	0.01
3												
4												
5												
6												
7												
8												
9												

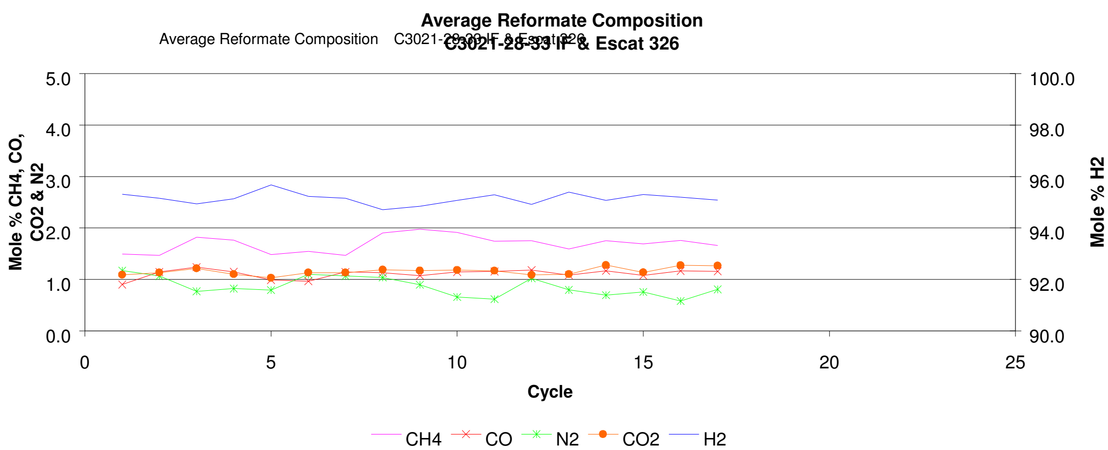
CO_2 Sorption Catalyst	C3021-28-33 IF
Reforming Catalyst: 0.5% rhodium o	Escat 326
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3)	
Batch No.	HCl178144D
Extruded by	RTC
Powder Post Processed	500.0
Calcined, C	2 hrs @ 450°C

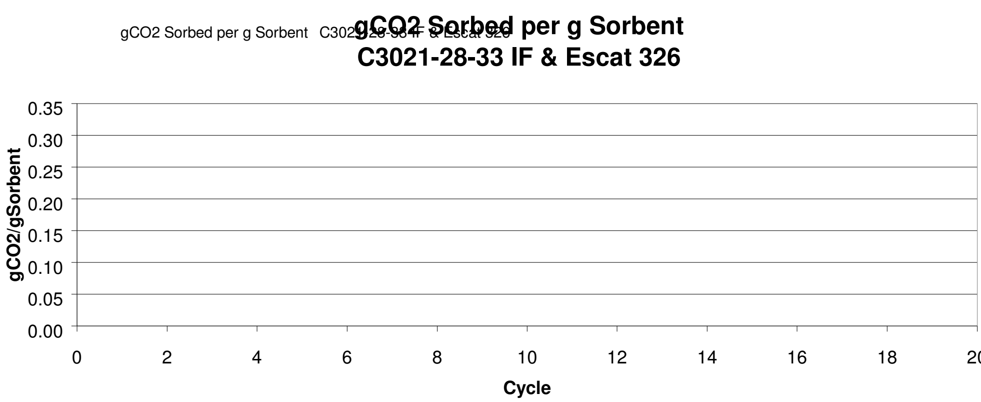
Wt. CO2 extrudate, g	22.11
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.7
SMR Cat. Wt., g	4.50
SMR Cat. Vol, cc	7.5
Density SMR, g/cc	0.6
Total Bed wt., g	26.61
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	95.3	1.5	0.9	1.2	1.1	1089.37	96.3%	94.2%	95.3%	5.67	0.0050	0.06
2	95.2	1.5	1.1	1.1	1.1	1269.14	95.3%	94.3%	95.0%	5.70	0.0049	0.06
3	94.9	1.8	1.2	0.8	1.2	551.29	94.8%	93.0%	94.6%	7.41	0.0048	0.07
4	95.1	1.8	1.1	0.8	1.1	730.68	95.2%	93.2%	95.2%	6.26	0.0049	0.06
5	95.7	1.5	1.0	0.8	1.0	909.16	95.9%	94.2%	95.6%	5.19	0.0050	0.06
6	95.2	1.5	1.0	1.1	1.1	1074.87	96.0%	94.0%	95.1%	6.15	0.0050	0.06
7	95.2	1.5	1.1	1.1	1.1	1269.14	95.3%	94.3%	95.0%	5.70	0.0049	0.06
8	94.7	1.9	1.1	1.0	1.2	1629.61	95.3%	92.7%	94.8%	5.14	0.0048	0.05
9	94.8	2.0	1.1	0.9	1.2	1809.29	95.5%	92.4%	94.9%	5.19	0.0048	0.05
10	95.1	1.9	1.1	0.7	1.2	1989.61	95.2%	92.6%	94.8%	4.56	0.0048	0.04
11	95.3	1.7	1.2	0.6	1.2	2169.32	95.2%	93.3%	94.9%	4.58	0.0049	0.04
12	94.9	1.8	1.2	1.0	1.1	2349.03	95.1%	93.2%	95.3%	4.55	0.0049	0.04
13	95.4	1.6	1.1	0.8	1.1	2528.62	95.5%	93.8%	95.2%	4.59	0.0049	0.05
14	95.1	1.8	1.2	0.7	1.3	3039.51	95.1%	93.2%	94.4%	4.75	0.0048	0.04
15	95.3	1.7	1.1	0.8	1.1	2889.00	95.5%	93.5%	95.1%	4.64	0.0049	0.05
16	95.2	1.8	1.2	0.6	1.3	3069.49	95.2%	93.2%	94.4%	4.54	0.0048	0.04
17	95.1	1.7	1.2	0.8	1.3	3249.54	95.2%	93.6%	94.5%	4.45	0.0049	0.04


Average Reaction Efficiencies
C3021-28-33 IF & Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
2
4
6
8
10
12
14
16
18
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition
C3021-28-33 IF & Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
5
10
15
20
25
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent
C3021-28-33 IF & Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
14
16
18
20
Cycle

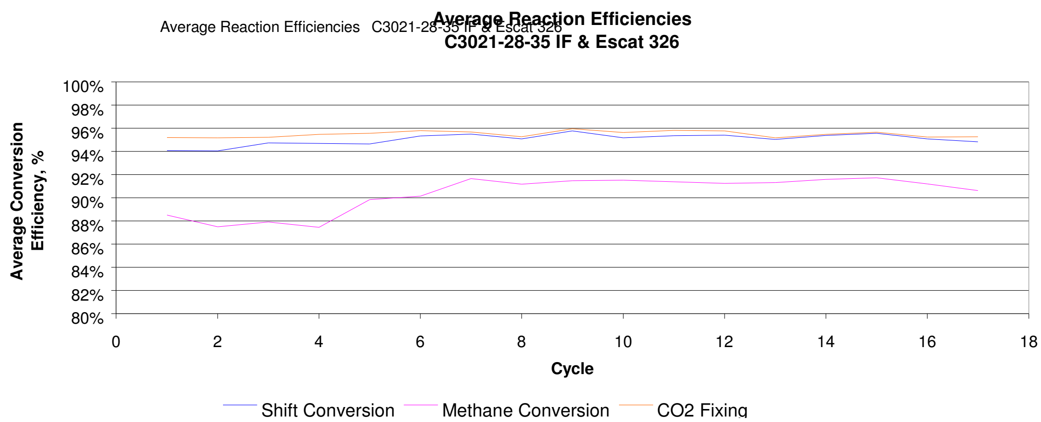
CO_2 Sorption Catalyst	C3021-28-35 IF
Reforming Catalyst: 0.5% rhodium o	Escat 326
Composition CO_2 sorb	90:10 wt/wt
(50:50CaO/MgO):(0.5wt%Rh/Al2O3)	
Batch No.	HCl178144E
Extruded by	RTC
Powder Post Processed	500.0
Calcined, C	2 hrs @ 450°C

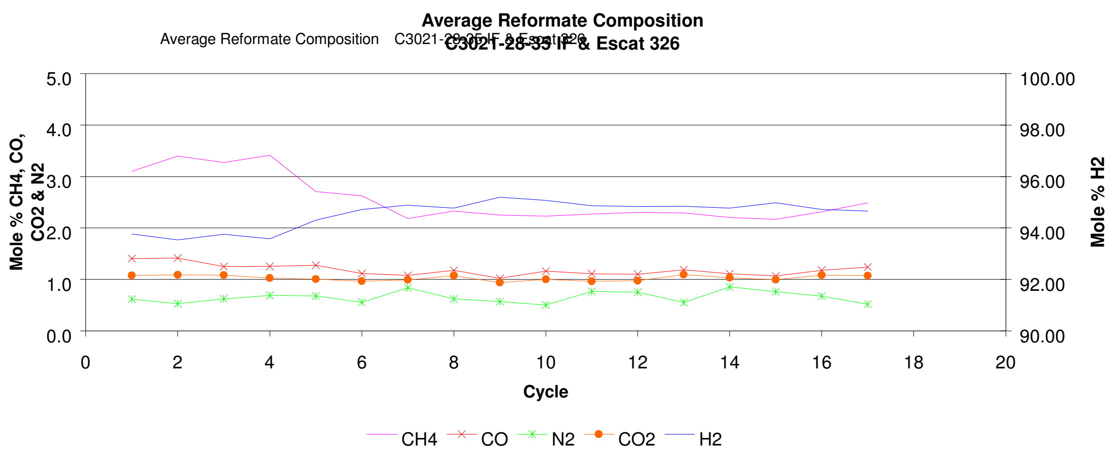
Wt. CO2 extrudate, g	27.11
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
SMR Cat. Wt., g	4.50
SMR Cat. Vol, cc	7.5
Density SMR, g/cc	0.6
Total Bed wt., g	31.61
Total Bed Vol., ml	40.0

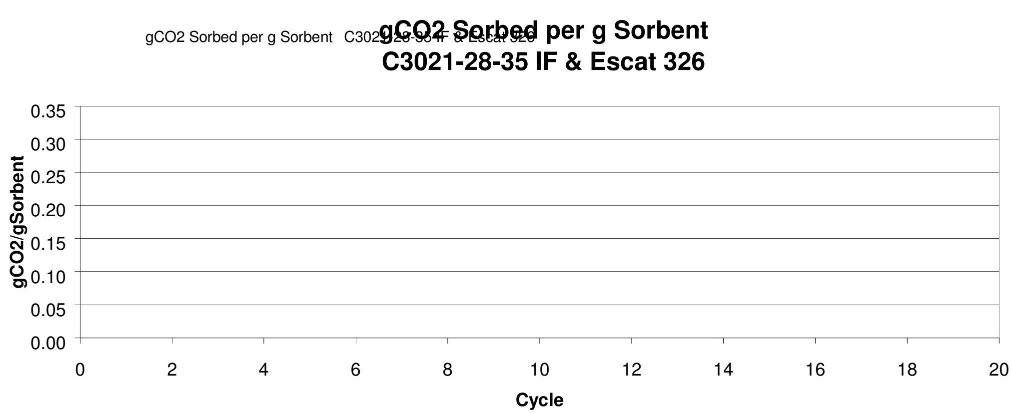
Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	93.77	3.10	1.41	0.62	1.08	196.72	94.07%	88.50%	95.20%	20.40	0.0037	0.08
2	93.5	3.4	1.4	0.5	1.1	375.79	94.0%	87.5%	95.2%	19.30	0.0037	0.07
3	93.8	3.3	1.2	0.6	1.1	556.02	94.7%	87.9%	95.2%	20.28	0.0037	0.08
4	93.6	3.4	1.3	0.7	1.0	735.40	94.7%	87.4%	95.5%	20.32	0.0037	0.08
5	94.3	2.7	1.3	0.7	1.0	915.64	94.7%	89.8%	95.6%	19.21	0.0038	0.07
6	94.7	2.6	1.1	0.6	1.0	1094.66	95.3%	90.1%	95.8%	18.05	0.0039	0.07
7	94.9	2.2	1.1	0.8	1.0	1274.50	95.5%	91.7%	95.7%	18.12	0.0039	0.07
8	94.8	2.3	1.2	0.6	1.1	1634.32	95.1%	91.2%	95.3%	18.05	0.0039	0.07
9	95.2	2.2	1.0	0.6	0.9	1814.06	95.8%	91.5%	96.0%	15.78	0.0040	0.06
10	95.1	2.2	1.2	0.5	1.0	1993.79	95.2%	91.5%	95.6%	15.91	0.0039	0.06
11	94.9	2.3	1.1	0.8	1.0	2173.50	95.4%	91.4%	95.8%	15.78	0.0039	0.06
12	94.8	2.3	1.1	0.8	1.0	2353.80	95.4%	91.2%	95.8%	14.85	0.0039	0.06
13	94.8	2.3	1.2	0.6	1.1	2533.98	95.0%	91.3%	95.2%	15.81	0.0039	0.06
14	94.8	2.2	1.1	0.9	1.0	2713.60	95.4%	91.6%	95.5%	15.96	0.0039	0.06
15	95.0	2.2	1.1	0.8	1.0	2893.19	95.6%	91.7%	95.7%	15.80	0.0040	0.06
16	94.7	2.3	1.2	0.7	1.1	3073.97	95.1%	91.2%	95.3%	14.87	0.0039	0.06
17	94.7	2.5	1.2	0.5	1.1	3254.04	94.8%	90.6%	95.3%	14.87	0.0039	0.06

APPENDIX E


Average Reaction Efficiencies C3021-28-35 IF & Escat 326
Average Reaction Efficiencies
C3021-28-35 IF & Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
2
4
6
8
10
12
14
16
18
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition C3021-28-35 IF & Escat 326
Average Reformate Composition
C3021-28-35 IF & Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
100.00
98.00
96.00
94.00
92.00
90.00
Mole % H2
0
2
4
6
8
10
12
14
16
18
20
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent C3021-28-35 IF & Escat 326
gCO2 Sorbed per g Sorbent
C3021-28-35 IF & Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
14
16
18
20
Cycle

CO_2 Sorption Catalyst	*C3021-39-32	*CSMP C3021-34-12	*CSMP C3021-34-12	*CSMP C3022-28-31	*CSMP C3022-30-32
Reforming Catalyst: 0.5% rhodium on Alumina)	**Engelhard Escat 326 (0.5%Rh on Alumina)**	**CSMP C3021-9-28 80:20 (PRA178137B (0.5%Rh/Al2O3)):Al2O3**	**Engelhard Escat 326 (0.5%Rh on Alumina)**	**Engelhard Escat 326 (0.5%Rh on Alumina)**	**Engelhard Escat 326 (0.5%Rh on Alumina)**
Composition CO_2 sorb	CaO/MgO (55:45)	CaO/MgO (55:45)	CaO/MgO(55:45)	CaO/MgO (55:45)	
Binder	15%Al203	15%Al203	15%Al203	15%Al203	
Batch No.	HCM178165E	PRA178137B	HCM178165E	HCM178173B	HCM178163C
Extruded by	RTC	RTC	RTC	RTC	RTC
Oven Atmosphere	Air	Air	Air	Air	Air
Calcined, C	500C	2 hrs @ 750C	2 hrs @ 750C	750	
Wt. CO2 extrudate, g	29.0	20.0	22.1	26.0	26.0
Vol. CO2 extrudate, cc	33.4	36.0	36.5	34.0	32.5
Density CO2, g/cc	0.9	0.6	0.6	0.8	0.8
Wt. SMR Cat., g	5.83	4.0	4.4	5.2	4.5
Vol. SMR Cat., cc	9.32	5.8	7.6	8.7	7.5
Density SMR, g/cc	0.6	0.7	0.6	0.6	0.6
Total Bed Wt., g	34.8	24.0	26.5	31.2	30.5
Total Bed Vol., ml	42.7	41.8	40.0	40.0	40.0
Reactor	R1	R1	R2	R1	R1
S/C	3	3	3	3	3
GHSV, hr-1	390	390	390	390	390
Reforming, °C	600	600	600	600	600
Calcination, °C	755	750	800	800	800
Pressure, atm.	1	1	1	1	1
Date loaded	2/4/04	37914	02/23/04	6/15/04	7/27/04
Date unloaded	2/12/04	37914	03/01/04	7/15/04	8/1/04
Sample	Extrudate	Extrudate	Extrudate	Extrudate	Extrudate
Post Run Description		All Cycles <90% H2	No powder		No powder
Size			All extrudates 1/2 length		Normal size
Discoloration			or more		Slight discoloration
***Large Batch Extrusion**					

CO_2 Sorption Catalyst	*CSMP C3022-42-33	*CSMP C3022-44-31	*CSMP C3022-47-23	*CSMP C3022-5-12
Reforming Catalyst: 0.5% rhodium on Alumina)	**Engelhard Escat 326 (0.5%Rh on Alumina)**	**Engelhard Escat 326 (0.5%Rh on Alumina)**	**Engelhard Escat 326 (0.5%Rh on Alumina)**	**Engelhard Escat 326 (0.5%Rh on Alumina)**
Composition CO_2 sorb	CaO/MgO (80/20)	CaO/MgO (83/17)	CaO/MgO(59:41)	CaO/MgO (55:45)
Binder	15%Al203	15%Al203	15%Al203	15%Al203
Batch No.	HCM178177A	HCM178177B	HCM1781177E	HCM178165E
Extruded by	RTC	RTC	RTC	RTC
Oven Atmosphere	Air	Air	Air	Air
Calcined, C	750 C; CS - 5.8 lbs/mm	750 C; CS - 4 lbs/mm	750 C; CS - 3 lbs/mm	750 C
Wt. CO2 extrudate, g	25.4	27.0	24.7	26.0
Vol. CO2 extrudate, cc	32.5	32.5	32.5	32.5
Density CO2, g/cc	0.8	0.8	0.8	0.8
Wt. SMR Cat., g	4.5	4.5	4.5	4.5
Vol. SMR Cat., cc	7.5	7.5	7.5	7.5
Density SMR, g/cc	0.6	0.6	0.6	0.6
Total Bed Wt., g	29.9	31.5	29.2	24.1
Total Bed Vol., ml	40.0	40.0	40.0	40.0
Reactor	R1	R2	R1	R1
S/C	3	3	3	3
GHSV, hr-1	390	390	390	390
Reforming, °C	600	600	600	600
Calcination, °C	800	800	800	800
Pressure, atm.	1	1	1	1
Date loaded	8/19/04	8/19/04	10/12/04	5/4/04
Date unloaded	9/8/04	9/8/04	11/3/04	5/20/04
Sample	Extrudate	Extrudate	Extrudate	Extrudate
Post Run Description	Mostly powder		No powder	
Size	No original size extrudates		Normal size	
Discoloration			Heavy toasted	
***Large Batch Extrusion**				

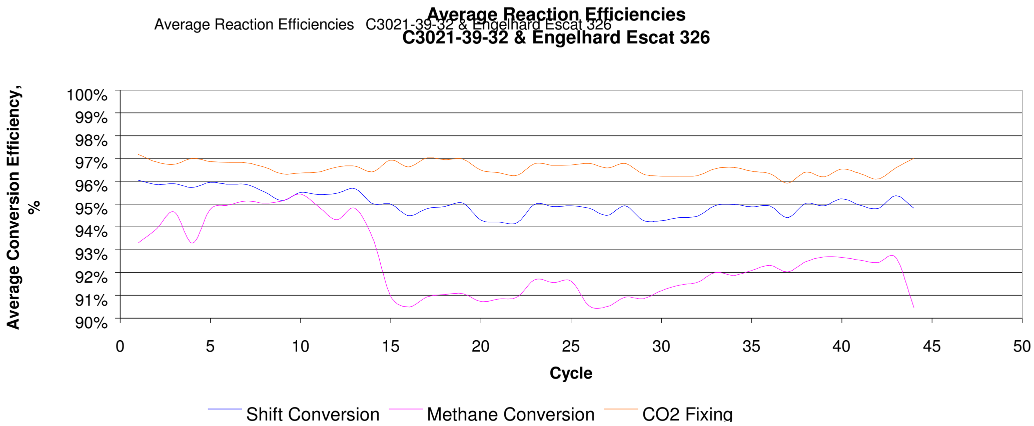
CO_2 Sorption Catalyst	C3021-39-32
Reforming Catalyst: 0.5% rhodium o	Engelhard Escat 326
Composition CO_2 sorb	CaO/MgO (55:45)
Binder	15% Al2O3
Batch No.	HCM178165E
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	500C

Wt. CO2 extrudate, g	29.0
Vol. CO2 extrudate, cc	33.4
Density CO2, g/cc	0.9
Wt. SMR Cat., g	5.8
Vol. SMR Cat., cc	9.3
Density SMR, g/cc	0.6
Total Bed Wt., g	34.8
Total Bed Vol., ml	42.7

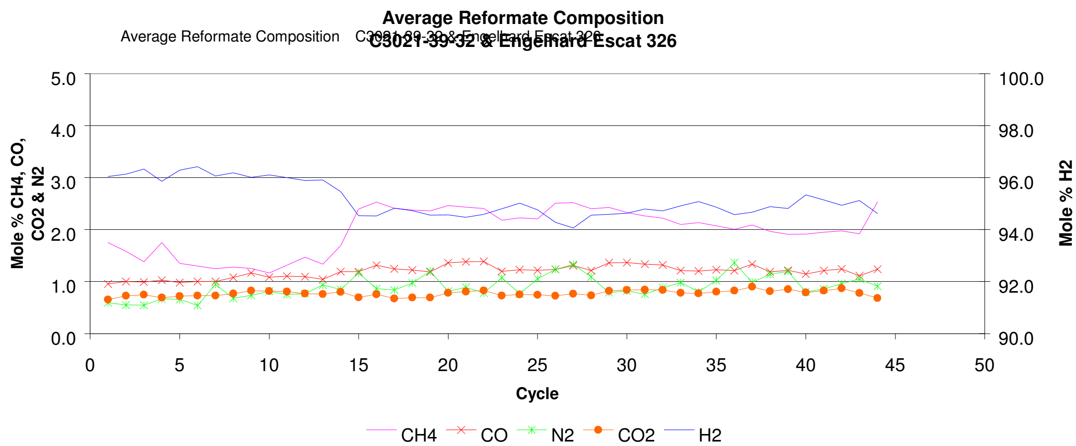
Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	755
Pressure, atm	1.0

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	96.0	1.8	1.0	0.6	0.7	208.30	96.0%	93.3%	97.2%	37.22	0.0038	0.14
2	96.1	1.6	1.0	0.6	0.7	397.94	95.9%	93.9%	96.8%	36.03	0.0038	0.14
3	96.3	1.4	1.0	0.5	0.7	587.09	95.9%	94.7%	96.7%	33.97	0.0038	0.13
4	95.9	1.8	1.0	0.7	0.7	776.32	95.7%	93.3%	97.0%	31.83	0.0038	0.12
5	96.3	1.3	1.0	0.7	0.7	964.86	96.0%	94.8%	96.9%	30.91	0.0039	0.12
6	96.4	1.3	1.0	0.5	0.7	1157.11	95.9%	95.0%	96.8%	28.63	0.0039	0.11
7	96.1	1.2	1.0	0.9	0.7	1320.33	95.9%	95.1%	96.8%	26.44	0.0039	0.10
8	96.2	1.3	1.1	0.7	0.8	1484.75	95.5%	95.0%	96.6%	24.59	0.0038	0.09
9	96.0	1.3	1.2	0.7	0.8	1649.57	95.2%	95.1%	96.3%	23.85	0.0038	0.09
10	96.1	1.2	1.1	0.8	0.8	1813.76	95.5%	95.4%	96.4%	24.01	0.0038	0.09
11	96.0	1.3	1.1	0.8	0.8	1978.59	95.4%	94.9%	96.4%	22.63	0.0038	0.09
12	95.9	1.5	1.1	0.8	0.8	2143.40	95.5%	94.3%	96.6%	21.17	0.0038	0.08
13	95.9	1.3	1.0	0.9	0.8	2307.48	95.7%	94.8%	96.7%	21.24	0.0038	0.08
14	95.5	1.7	1.2	0.8	0.8	2473.03	95.0%	93.5%	96.4%	21.17	0.0038	0.08
15	94.5	2.4	1.2	1.2	0.7	2637.60	95.0%	91.0%	96.9%	19.78	0.0037	0.07
16	94.5	2.5	1.3	0.9	0.8	2802.95	94.5%	90.5%	96.6%	19.78	0.0038	0.08
17	94.8	2.4	1.2	0.8	0.7	96.48	94.8%	90.9%	97.0%	18.28	0.0037	0.07
18	94.7	2.4	1.2	1.0	0.7	250.26	94.9%	91.0%	96.9%	18.44	0.0037	0.07
19	94.6	2.4	1.2	1.2	0.7	405.12	95.0%	91.1%	97.0%	17.54	0.0037	0.06
20	94.6	2.5	1.4	0.8	0.8	560.88	94.3%	90.7%	96.5%	17.74	0.0036	0.06
21	94.5	2.4	1.4	0.9	0.8	715.98	94.2%	90.8%	96.4%	17.58	0.0036	0.06
22	94.6	2.4	1.4	0.8	0.8	870.80	94.2%	90.9%	96.3%	17.60	0.0036	0.06
23	94.8	2.2	1.2	1.1	0.7	1024.59	95.0%	91.7%	96.8%	17.53	0.0037	0.06
24	95.0	2.2	1.2	0.8	0.8	1180.08	94.9%	91.6%	96.7%	15.78	0.0037	0.06
25	94.8	2.2	1.2	1.1	0.7	1334.78	94.9%	91.6%	96.7%	16.05	0.0037	0.06
26	94.3	2.5	1.2	1.2	0.7	1489.36	94.8%	90.5%	96.8%	16.90	0.0036	0.06
27	94.1	2.5	1.3	1.3	0.8	1644.28	94.5%	90.5%	96.6%	17.60	0.0036	0.06
28	94.6	2.4	1.2	1.1	0.7	1799.25	94.9%	90.9%	96.8%	15.74	0.0037	0.06
29	94.6	2.4	1.4	0.8	0.8	1955.05	94.3%	90.9%	96.3%	15.84	0.0036	0.06
30	94.6	2.3	1.4	0.8	0.8	2110.12	94.3%	91.2%	96.2%	15.76	0.0036	0.06
31	94.8	2.3	1.3	0.8	0.8	2264.78	94.4%	91.4%	96.2%	15.82	0.0036	0.06
32	94.7	2.2	1.3	0.9	0.8	2419.66	94.5%	91.6%	96.3%	15.77	0.0036	0.06
33	94.9	2.1	1.2	1.0	0.8	2573.87	94.9%	92.0%	96.6%	15.78	0.0037	0.06
34	95.1	2.1	1.2	0.8	0.8	2729.30	95.0%	91.9%	96.6%	14.06	0.0037	0.05
35	94.9	2.1	1.2	1.0	0.8	2883.82	94.9%	92.1%	96.4%	15.85	0.0037	0.06
36	94.6	2.0	1.2	1.4	0.8	3038.65	94.9%	92.3%	96.3%	15.82	0.0037	0.06
37	94.7	2.1	1.3	1.0	0.9	3194.71	94.4%	92.0%	95.9%	15.60	0.0036	0.06
38	94.9	2.0	1.2	1.1	0.8	3348.72	95.0%	92.5%	96.4%	15.61	0.0037	0.06
39	94.8	1.9	1.2	1.2	0.9	3504.08	94.9%	92.7%	96.2%	15.48	0.0037	0.06
40	95.3	1.9	1.1	0.8	0.8	3658.89	95.2%	92.7%	96.5%	14.14	0.0037	0.05
41	95.1	2.0	1.2	0.9	0.8	3814.34	95.0%	92.5%	96.3%	14.15	0.0037	0.05
42	94.9	2.0	1.2	1.0	0.9	3968.99	94.8%	92.4%	96.1%	15.51	0.0037	0.06
43	95.1	1.9	1.1	1.0	0.8	4123.69	95.4%	92.6%	96.6%	14.14	0.0037	0.05
44	94.6	2.5	1.2	0.9	0.7	4276.77	94.8%	90.5%	97.0%	14.07	0.0036	0.05

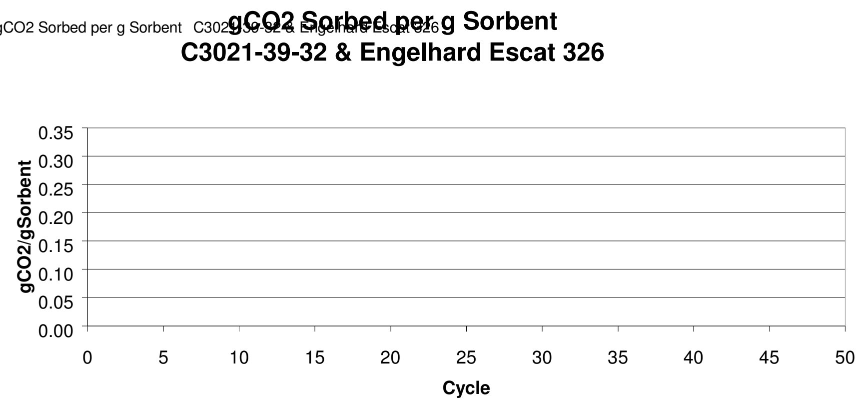
Average Reaction Efficiencies C3021-39-32 & Engelhard Escat 326



Average Reformate Composition C3021-39-32 & Engelhard Escat 326



gCO2 Sorbed per g Sorbent C3021-39-32 & Engelhard Escat 326

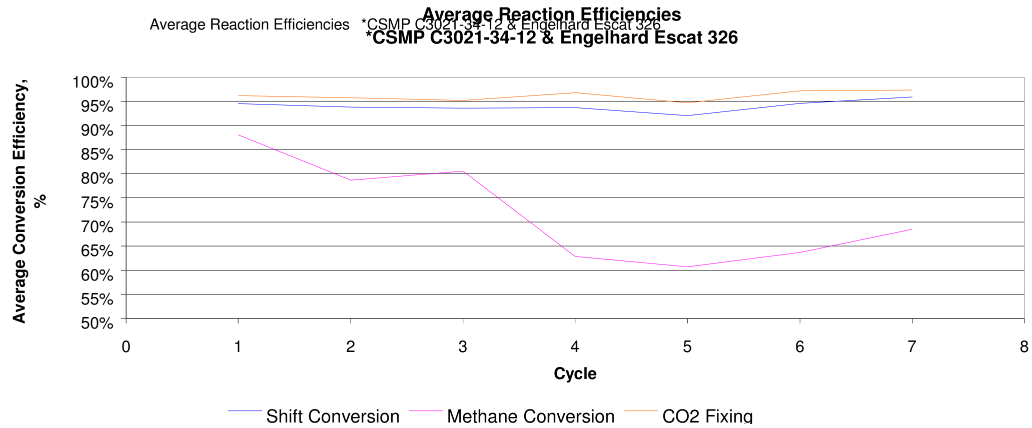


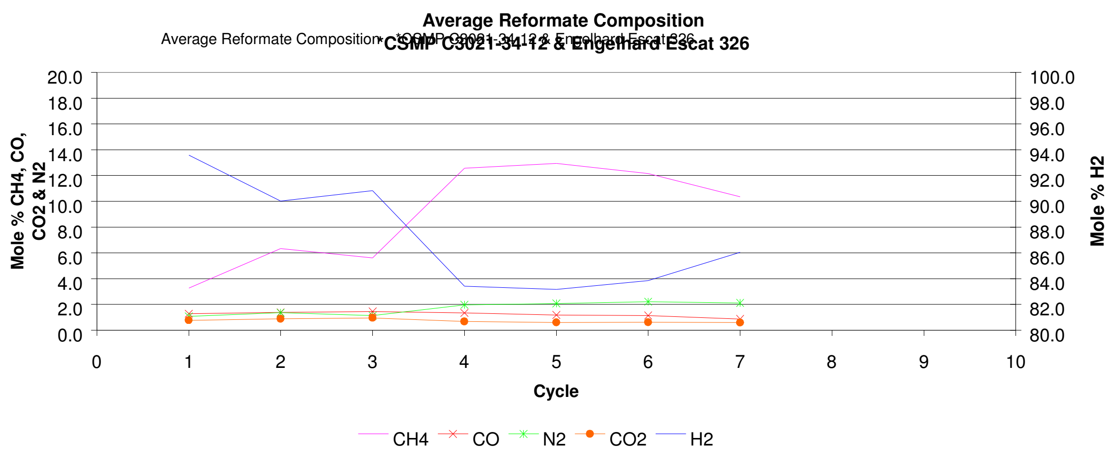
CO_2 Sorption Catalyst	*CSMP C3021-34-12
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/MgO(55:45)
Binder	15%Al203
Batch No.	HCM178165E
Extruded by	RTC
Oven Atmosphere	
Calcined, C	2 hrs @ 750C

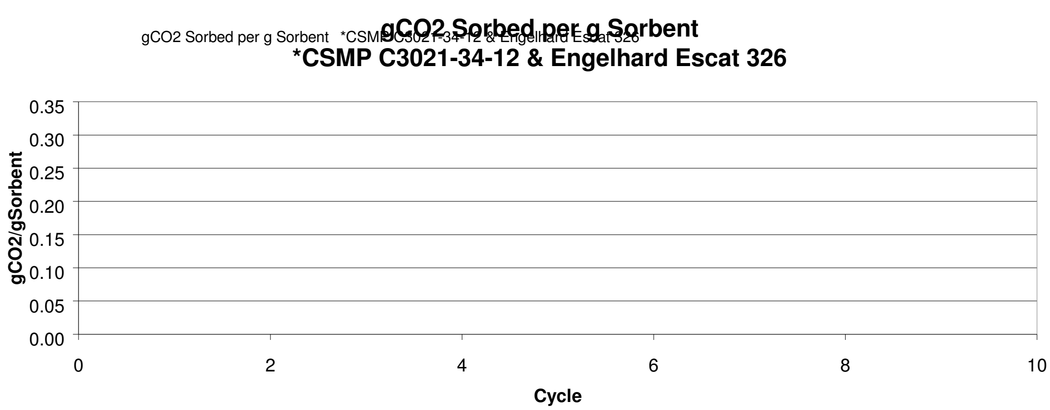
Wt. CO2 extrudate, g	21.3
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.7
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	25.8
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1.0

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2/gSorb
1	93.6	3.3	1.3	1.1	0.8	266.91	94.5%	88.0%	96.2%	41.38	0.0047	0.19
2	90.0	6.3	1.4	1.4	0.9	437.24	93.8%	78.7%	95.7%	39.88	0.0041	0.16
3	90.8	5.6	1.5	1.1	1.0	606.42	93.6%	80.5%	95.2%	37.39	0.0042	0.16
4	83.4	12.6	1.3	2.0	0.7	781.42	93.7%	62.8%	96.8%	44.75	0.0033	0.15
5	83.2	12.9	1.2	2.1	0.6	948.38	92.0%	60.7%	94.7%	39.88	0.0032	0.13
6	83.8	12.2	1.2	2.2	0.6	1117.98	94.6%	63.7%	97.2%	39.27	0.0034	0.13
7	86.0	10.3	0.9	2.1	0.6	1281.80	95.9%	68.5%	97.3%	28.78	0.0037	0.11


Average Reaction Efficiencies *CSMP C3021-34-12 & Engelhard Escat 326
Average Reaction Efficiencies
*CSMP C3021-34-12 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
65%
60%
55%
50%
0
1
2
3
4
5
6
7
8
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *CSMP C3021-34-12 & Engelhard Escat 326
Average Reformate Composition
*CSMP C3021-34-12 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
88.0
86.0
84.0
82.0
80.0
0
1
2
3
4
5
6
7
8
9
10
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent *CSMP C3021-34-12 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*CSMP C3021-34-12 & Engelhard Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
Cycle

CO_2 Sorption Catalyst	*CSMP C3021-34-12
Reforming Catalyst: 0.5% rhodium or	*CSMP C3021-9-28
Composition CO_2 sorb	CaO/MgO (55:45)
Binder	15%Al203
Batch No.	PRA178137B
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	2 hrs @ 750C

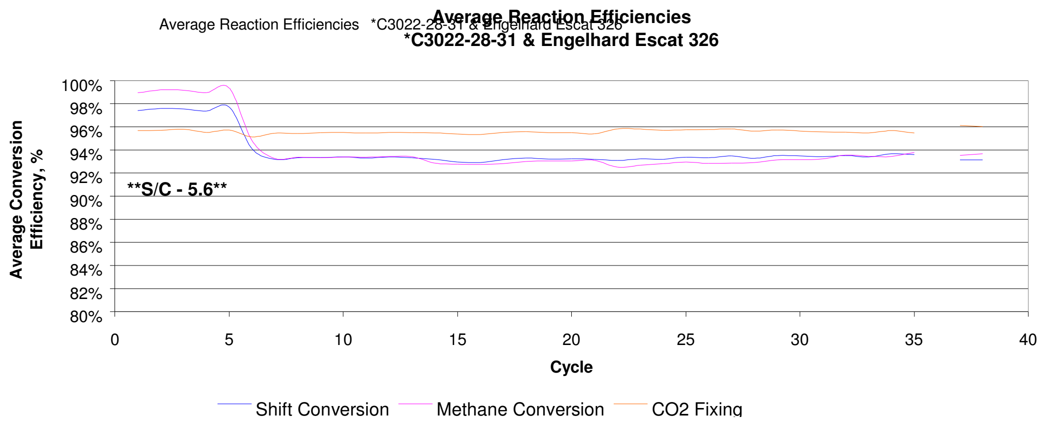
Wt. CO2 extrudate, g	29.0
Vol. CO2 extrudate, cc	33.4
Density CO2, g/cc	0.9
Wt. SMR Cat., g	5.8
Vol. SMR Cat., cc	9.3
Density SMR, g/cc	0.6
Total Bed Wt., g	34.8
Total Bed Vol., ml	42.7

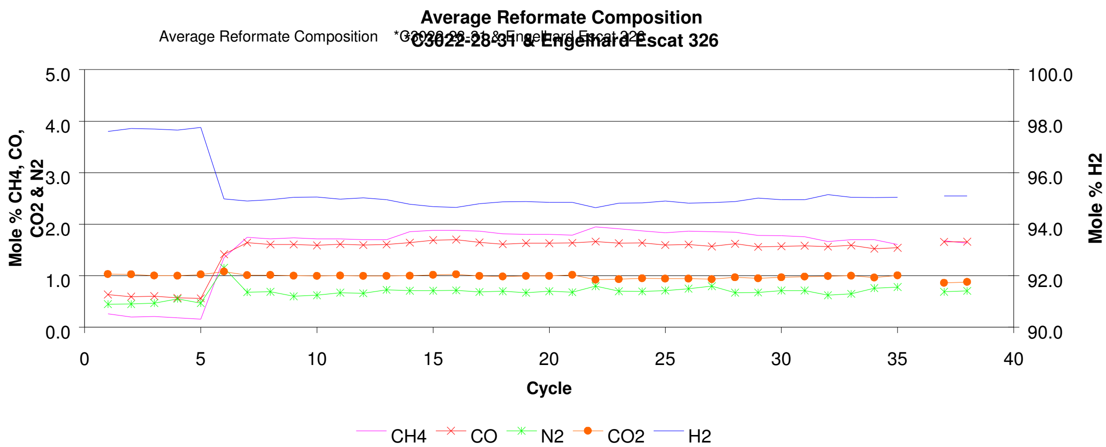
Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	755
Pressure, atm	1.0

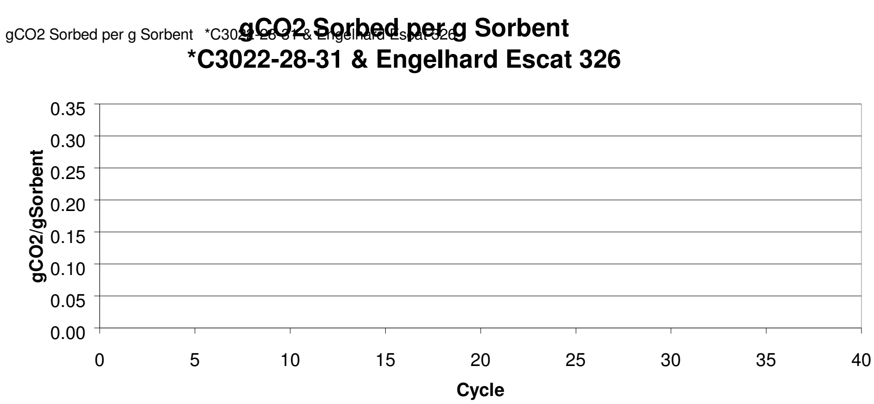
Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	90.0	5.5	1.7	2.1	0.7	271.19	92.4%	81.1%	96.5%			
2	87.2	5.4	3.5	2.1	1.7	122.92	74.7%	72.3%	78.3%			
3	88.5	3.5	4.6	1.5	1.9	252.53	80.1%	87.1%	89.6%			

CO_2 Sorption Catalyst	*C3022-28-31	Wt. CO2 extrudate, g	26.0	Reactor	R1
Reforming Catalyst: 0.5% rhodium o	Engelhard Escat 326	Vol. CO2 extrudate, cc	34.0	S/C	3
Composition CO_2 sorb	CaO/MgO (55:45)	Density CO2, g/cc	0.8	GHSV, hr-1	390
Binder	15%Al203	Wt. SMR Cat., g	5.2	Reforming, °C	600
Batch No.	HCM178173B	Vol. SMR Cat., cc	8.7	Calcination, °C	800
Extruded by	RTC	Density SMR, g/cc	0.6	Pressure, atm.	1.0
Oven Atmosphere	Air	Total Bed Wt., g	31.2		
Calcined, C	750.0	Total Bed Vol., ml	40.0		

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CE	Cycle Time	S	gCO2/gSorb	
1	97.6	0.3	0.6	0.4	1.0	217.47	97.4%	98.9%	95.7%	60.12	0.0045	0.27	
2	97.7	0.2	0.6	0.5	1.0	397.93	97.6%	99.2%	95.7%	59.63	0.0045	0.27	
3	97.7	0.2	0.6	0.5	1.0	578.28	97.5%	99.2%	95.8%	59.36	0.0046	0.27	**S/C**
4	97.7	0.2	0.6	0.6	1.0	758.00	97.4%	99.0%	95.5%	59.73	0.0045	0.27	5.60
5	97.8	0.2	0.6	0.5	1.0	938.44	97.7%	99.4%	95.7%	59.06	0.0046	0.27	5.60
6	95.0	1.3	1.4	1.2	1.1	1116.79	94.1%	94.8%	95.1%	60.54	0.0042	0.25	5.60
7	94.9	1.7	1.6	0.7	1.0	1345.06	93.2%	93.3%	95.4%	55.44	0.0041	0.23	5.60
8	95.0	1.7	1.6	0.7	1.0	1541.90	93.3%	93.4%	95.4%	54.62	0.0041	0.22	5.60
9	95.0	1.7	1.6	0.6	1.0	1731.25	93.3%	93.3%	95.5%	52.31	0.0041	0.21	
10	95.1	1.7	1.6	0.6	1.0	1920.70	93.4%	93.4%	95.5%	50.82	0.0041	0.21	
11	95.0	1.7	1.6	0.7	1.0	2110.43	93.3%	93.4%	95.5%	49.94	0.0041	0.20	
12	95.0	1.7	1.6	0.7	1.0	2299.54	93.4%	93.4%	95.5%	49.32	0.0041	0.20	
13	95.0	1.7	1.6	0.7	1.0	2489.59	93.3%	93.4%	95.5%	49.02	0.0041	0.20	
14	94.8	1.9	1.6	0.7	1.0	2679.23	93.2%	92.9%	95.5%	48.93	0.0041	0.20	
15	94.7	1.9	1.7	0.7	1.0	2869.21	93.0%	92.8%	95.4%	47.59	0.0040	0.19	
16	94.7	1.9	1.7	0.7	1.0	3058.52	92.9%	92.8%	95.3%	47.69	0.0040	0.19	
17	94.8	1.9	1.6	0.7	1.0	3248.55	93.2%	92.8%	95.5%	46.27	0.0041	0.19	
18	94.9	1.8	1.6	0.7	1.0	3437.77	93.3%	93.0%	95.6%	46.29	0.0041	0.19	
19	94.9	1.8	1.6	0.7	1.0	3628.12	93.2%	93.1%	95.5%	45.46	0.0041	0.19	
20	94.9	1.8	1.6	0.7	1.0	3818.13	93.2%	93.0%	95.5%	45.49	0.0041	0.19	
21	94.9	1.8	1.6	0.7	1.0	4007.81	93.2%	93.1%	95.4%	45.54	0.0041	0.19	
22	94.6	2.0	1.7	0.8	0.9	137.27	93.1%	92.5%	95.8%	45.22	0.0041	0.18	
23	94.8	1.9	1.6	0.7	0.9	316.64	93.2%	92.7%	95.8%	44.46	0.0041	0.18	
24	94.8	1.9	1.6	0.7	1.0	496.65	93.2%	92.8%	95.7%	43.66	0.0041	0.18	
25	94.9	1.8	1.6	0.7	0.9	675.96	93.4%	92.9%	95.7%	43.74	0.0041	0.18	
26	94.8	1.9	1.6	0.7	0.9	855.70	93.3%	92.8%	95.8%	42.58	0.0041	0.17	
27	94.8	1.9	1.6	0.8	0.9	1035.48	93.5%	92.9%	95.8%	41.59	0.0041	0.17	
28	94.9	1.8	1.6	0.7	1.0	1215.75	93.3%	92.9%	95.6%	41.59	0.0041	0.17	
29	95.0	1.8	1.6	0.7	1.0	1395.49	93.5%	93.1%	95.7%	40.21	0.0041	0.16	
30	95.0	1.8	1.6	0.7	1.0	1575.04	93.5%	93.1%	95.6%	41.22	0.0041	0.17	
31	95.0	1.8	1.6	0.7	1.0	1664.04	93.4%	93.2%	95.6%	41.19	0.0041	0.17	
32	95.1	1.7	1.6	0.6	1.0	1935.01	93.5%	93.6%	95.5%	40.21	0.0041	0.17	
33	95.1	1.7	1.6	0.6	1.0	2115.05	93.4%	93.4%	95.5%	39.99	0.0041	0.16	
34	95.0	1.7	1.5	0.8	1.0	2294.08	93.7%	93.4%	95.7%	40.08	0.0041	0.16	
35	95.0	1.6	1.5	0.8	1.0	2474.25	93.6%	93.8%	95.5%	40.12	0.0041	0.17	
36													
37	95.1	1.7	1.7	0.7	0.9	2834.66	93.1%	93.5%	96.1%	39.61	0.0041	0.16	
38	95.1	1.6	1.7	0.7	0.9	3014.96	93.1%	93.7%	96.0%	38.79	0.0041	0.16	


Average Reaction Efficiencies *C3022-28-31 & Engelhard Escat 326
Average Reaction Efficiencies
*C3022-28-31 & Engelhard Escat 326
Average Conversion Efficiency, %
S/C - 5.6
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *C3022-28-31 & Engelhard Escat 326
Average Reformate Composition
*C3022-28-31 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
Cycle
CH4
CO
N2
CO2
H2

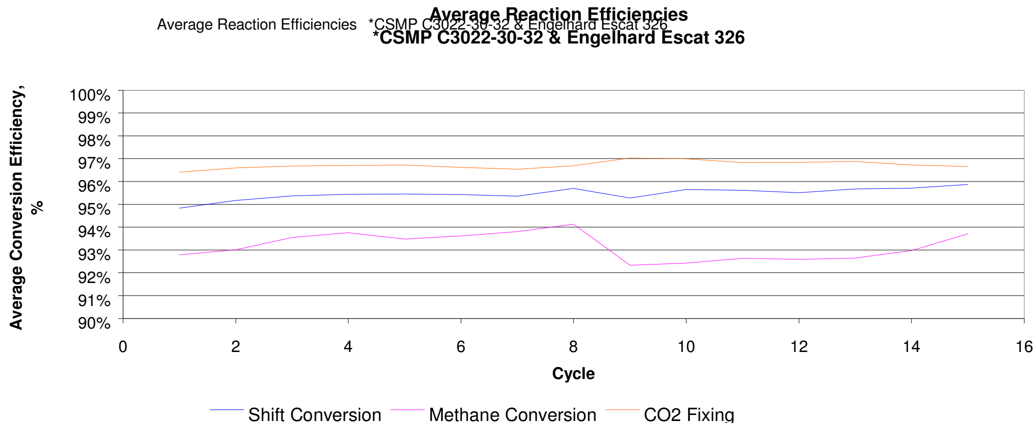

gCO2 Sorbed per g Sorbent *C3022-28-31 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*C3022-28-31 & Engelhard Escat 326
gCO2/gSorbent
Cycle

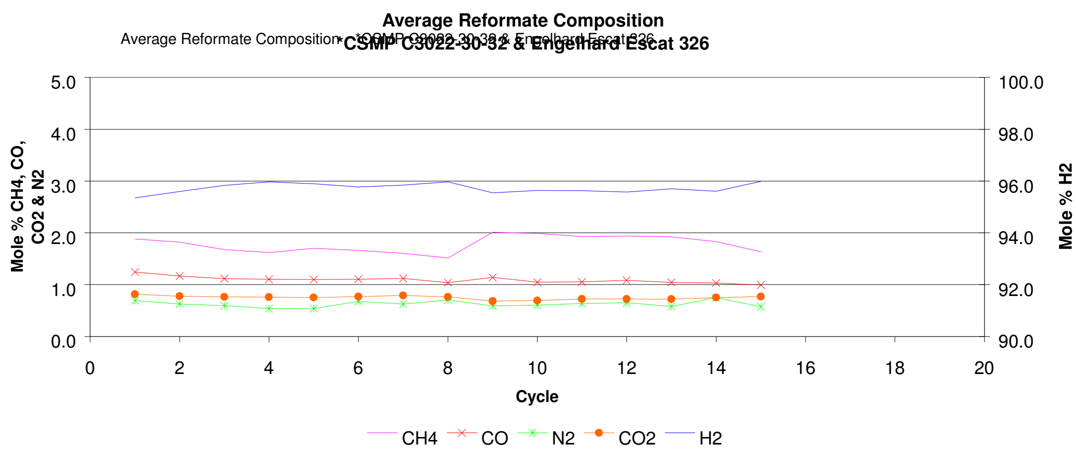
CO_2 Sorption Catalyst	*CSMP C3022-30-32
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	
Binder	
Batch No.	HCM178163C
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	

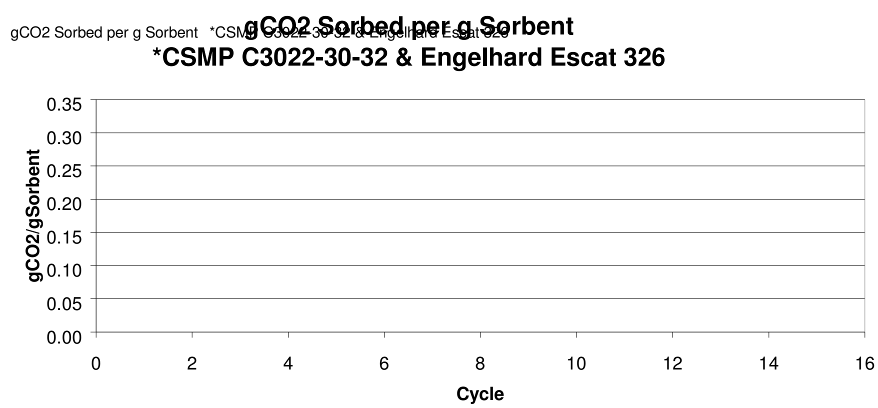
Wt. CO2 extrudate, g	26.0
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	30.5
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1.0

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	95.4	1.9	1.2	0.7	0.8	234.52	94.8%	92.8%	96.4%	59.00	0.0042	0.25
2	95.6	1.8	1.2	0.6	0.8	412.52	95.2%	93.0%	96.6%	55.00	0.0042	0.23
3	95.8	1.7	1.1	0.6	0.8	591.02	95.4%	93.5%	96.7%	52.00	0.0042	0.22
4	96.0	1.6	1.1	0.5	0.8	770.02	95.4%	93.8%	96.7%	50.00	0.0043	0.21
5	95.9	1.7	1.1	0.5	0.8	949.02	95.5%	93.5%	96.7%	48.00	0.0042	0.20
6	95.8	1.7	1.1	0.7	0.8	1128.02	95.4%	93.6%	96.6%	48.00	0.0042	0.20
7	95.8	1.6	1.1	0.6	0.8	1307.78	95.4%	93.8%	96.5%	46.81	0.0042	0.20
8	96.0	1.5	1.0	0.7	0.8	1486.44	95.7%	94.1%	96.7%	45.34	0.0043	0.19
9	95.5	2.0	1.1	0.6	0.7	1765.07	95.3%	92.3%	97.0%	41.66	0.0042	0.17
10	95.6	2.0	1.0	0.6	0.7	1943.73	95.7%	92.4%	97.0%	42.01	0.0042	0.18
11	95.6	1.9	1.1	0.6	0.7	2123.43	95.6%	92.6%	96.8%	41.87	0.0042	0.18
12	95.6	1.9	1.1	0.6	0.7	2302.67	95.5%	92.6%	96.8%	40.76	0.0042	0.17
13	95.7	1.9	1.0	0.6	0.7	2482.39	95.7%	92.6%	96.9%	38.50	0.0042	0.16
14	95.6	1.8	1.0	0.7	0.8	2661.73	95.7%	93.0%	96.7%	39.77	0.0042	0.17
15	96.0	1.6	1.0	0.6	0.8	2841.74	95.9%	93.7%	96.7%	37.40	0.0043	0.16


Average Reaction Efficiencies *CSMP C3022-30-32 & Engelhard Escat 326
Average Reaction Efficiencies
*CSMP C3022-30-32 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
99%
98%
97%
96%
95%
94%
93%
92%
91%
90%
0
2
4
6
8
10
12
14
16
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *CSMP C3022-30-32 & Engelhard Escat 326
Average Reformate Composition
*CSMP C3022-30-32 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
2
4
6
8
10
12
14
16
18
20
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent *CSMP C3022-30-32 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*CSMP C3022-30-32 & Engelhard Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
14
16
Cycle

CO_2 Sorption Catalyst	*CSMP C3022-42-33
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/MgO (80/20)
Binder	15%Al203
Batch No.	HCM178177A
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750 C

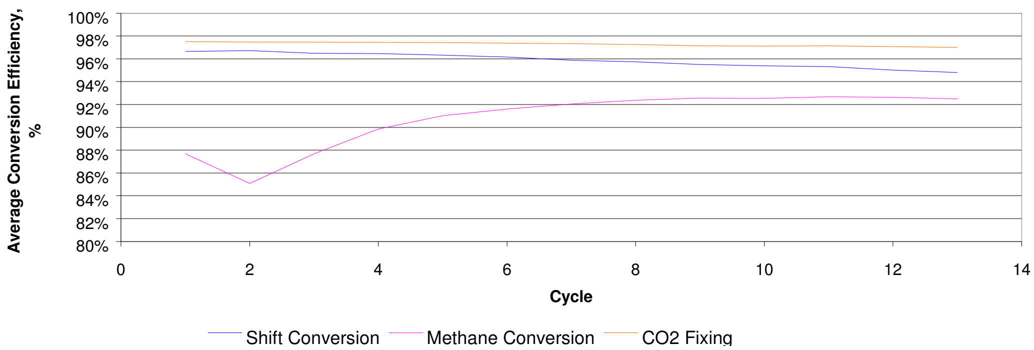
Wt. CO2 extrudate, g	25.4
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	29.9
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1.0

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	94.4	3.4	0.8	0.9	0.6	217.00	96.7%	87.7%	97.5%	60.00	0.00	0.25
2	93.5	4.1	0.8	0.9	0.6	396.00	96.7%	85.1%	97.5%	60.00	0.00	0.24
3	94.3	3.4	0.8	0.9	0.6	576.50	96.5%	87.7%	97.5%	61.00	0.00	0.25
4	95.2	2.7	0.8	0.7	0.6	756.00	96.5%	89.9%	97.5%	61.00	0.00	0.26
5	95.4	2.4	0.9	0.8	0.6	934.13	96.3%	91.0%	97.4%	61.00	0.00	0.26
6	95.6	2.2	0.9	0.7	0.6	1116.50	96.2%	91.6%	97.4%	61.00	0.00	0.26
7	95.6	2.1	1.0	0.7	0.6	1296.50	95.9%	92.0%	97.3%	61.00	0.00	0.26
8	95.7	2.0	1.0	0.6	0.6	1476.58	95.7%	92.4%	97.3%	59.91	0.00	0.26
9	95.7	1.9	1.1	0.6	0.7	1657.03	95.5%	92.6%	97.1%	60.35	0.00	0.26
10	95.7	2.0	1.1	0.5	0.7	1836.58	95.4%	92.5%	97.1%	60.20	0.00	0.26
11	95.8	1.9	1.1	0.5	0.7	2016.66	95.3%	92.7%	97.1%	59.97	0.00	0.26
12	95.6	1.9	1.2	0.5	0.7	2196.50	95.0%	92.6%	97.1%	60.14	0.00	0.26
13	95.5	2.0	1.3	0.5	0.7	2377.12	94.8%	92.5%	97.0%	60.18	0.00	0.26

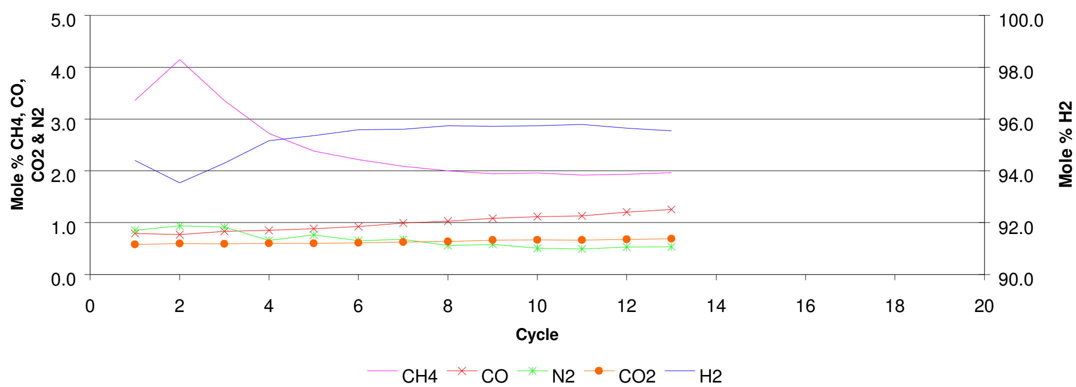
Average Reaction Efficiencies *CSMP C3022-42-33 & Engelhard Escat 326

Average Reaction Efficiencies
***CSMP C3022-42-33 & Engelhard Escat 326**



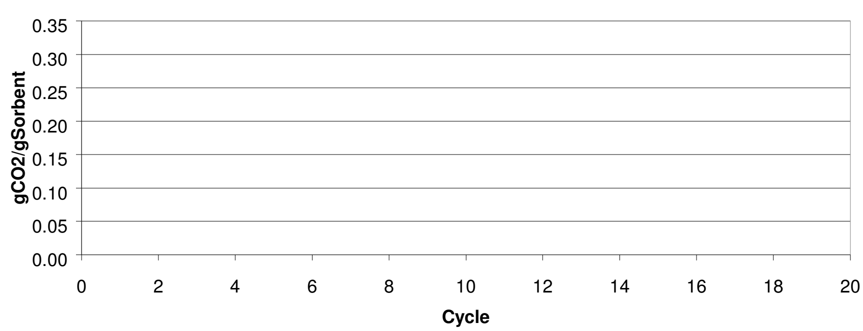
Average Reformate Composition *CSMP C3022-42-33 & Engelhard Escat 326

Average Reformate Composition
***CSMP C3022-42-33 & Engelhard Escat 326**



gCO2 Sorbed per g Sorbent *CSMP C3022-42-33 & Engelhard Escat 326

gCO2 Sorbed per g Sorbent
***CSMP C3022-42-33 & Engelhard Escat 326**

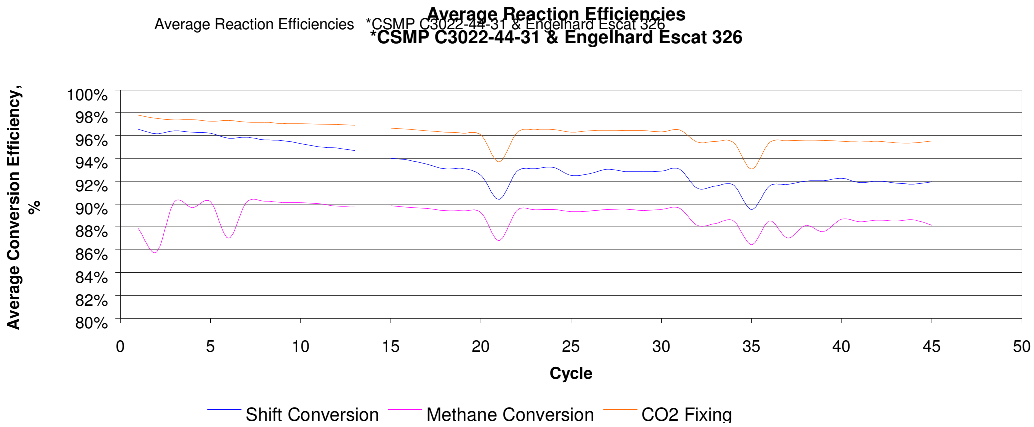


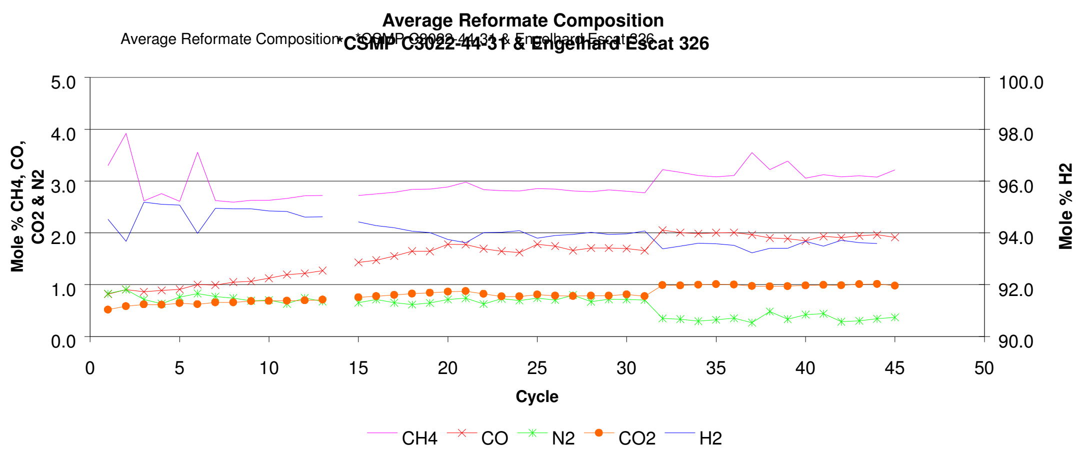
CO_2 Sorption Catalyst	*CSMP C3022-44-31
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/MgO (83/17)
Binder	15%Al203
Batch No.	HCM178177B
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750 C

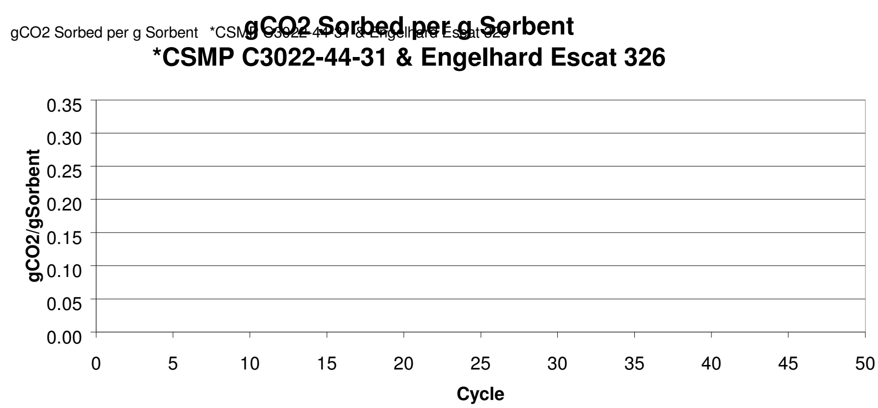
Wt. CO2 extrudate, g	27.0
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	31.5
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	94.5	3.3	0.8	0.8	0.5	216.49	96.6%	87.9%	97.8%	29.50	0.0039	0.23
2	93.7	3.9	0.9	0.9	0.6	395.99	96.2%	85.8%	97.5%	30.00	0.0038	0.23
3	95.2	2.6	0.9	0.7	0.6	576.99	96.4%	90.2%	97.4%	30.00	0.0040	0.24
4	95.1	2.8	0.9	0.6	0.6	756.99	96.3%	89.7%	97.4%	28.99	0.0040	0.23
5	95.1	2.6	0.9	0.8	0.6	936.49	96.2%	90.2%	97.3%	30.50	0.0040	0.24
6	94.0	3.6	1.0	0.8	0.6	1117.49	95.8%	87.0%	97.3%	29.50	0.0038	0.23
7	94.9	2.6	1.0	0.8	0.7	1296.49	95.9%	90.2%	97.2%	30.50	0.0040	0.24
8	94.9	2.6	1.0	0.7	0.7	1476.48	95.6%	90.3%	97.2%	30.03	0.0040	0.24
9	94.9	2.6	1.1	0.7	0.7	1656.92	95.6%	90.1%	97.1%	30.18	0.0040	0.24
10	94.8	2.6	1.1	0.7	0.7	1836.48	95.3%	90.1%	97.0%	30.05	0.0039	0.24
11	94.8	2.7	1.2	0.6	0.7	2016.56	95.0%	90.0%	97.0%	29.51	0.0039	0.23
12	94.6	2.7	1.2	0.7	0.7	2196.40	94.9%	89.8%	97.0%	30.12	0.0039	0.24
13	94.6	2.7	1.3	0.7	0.7	2377.02	94.7%	89.8%	96.9%	30.24	0.0039	0.23
15	94.4	2.7	1.4	0.7	0.8	2736.96	94.0%	89.8%	96.7%	29.83	0.0040	0.24
16	94.3	2.8	1.5	0.7	0.8	2917.06	93.8%	89.7%	96.6%	29.88	0.0040	0.24
17	94.2	2.8	1.6	0.6	0.8	3096.55	93.5%	89.6%	96.4%	29.21	0.0041	0.24
18	94.1	2.8	1.6	0.6	0.8	3276.85	93.1%	89.4%	96.3%	29.14	0.0041	0.24
19	94.0	2.8	1.6	0.6	0.8	3456.51	93.1%	89.4%	96.2%	30.01	0.0041	0.24
20	93.7	2.9	1.8	0.7	0.9	3636.82	92.5%	89.3%	96.1%	30.00	0.0041	0.24
21	93.6	3.0	1.8	0.7	0.9	3816.41	90.4%	86.8%	93.7%	29.18	0.0041	0.24
22	94.0	2.8	1.7	0.6	0.8	3994.48	92.9%	89.5%	96.3%	26.86	0.0041	0.22
23	94.0	2.8	1.6	0.7	0.8	4172.96	93.1%	89.5%	96.5%	25.44	0.0041	0.21
24	94.1	2.8	1.6	0.7	0.8	4352.03	93.2%	89.5%	96.5%	24.68	0.0041	0.20
25	93.8	2.9	1.8	0.7	0.8	4532.83	92.5%	89.4%	96.3%	25.27	0.0041	0.21
26	93.9	2.8	1.7	0.7	0.8	4711.70	92.7%	89.4%	96.4%	23.99	0.0041	0.20
27	93.9	2.8	1.7	0.8	0.8	4890.78	93.0%	89.5%	96.5%	24.02	0.0041	0.20
28	94.0	2.8	1.7	0.7	0.8	5070.59	92.8%	89.6%	96.4%	23.25	0.0041	0.19
29	93.9	2.8	1.7	0.7	0.8	5250.39	92.8%	89.4%	96.4%	22.58	0.0041	0.18
30	94.0	2.8	1.7	0.7	0.8	5429.53	92.9%	89.5%	96.3%	22.48	0.0041	0.18
31	94.1	2.8	1.7	0.7	0.8	5608.94	93.1%	89.7%	96.5%	21.77	0.0041	0.18
32	93.4	3.2	2.0	0.3	1.0	11718.28	91.4%	88.1%	95.4%	22.20	0.0041	0.18
33	93.5	3.2	2.0	0.3	1.0	11896.95	91.6%	88.3%	95.5%	21.75	0.0041	0.18
34	93.6	3.1	2.0	0.3	1.0	12077.32	91.7%	88.5%	95.4%	21.69	0.0041	0.18
35	93.6	3.1	2.0	0.3	1.0	12256.60	89.5%	86.5%	93.1%	21.61	0.0041	0.18
36	93.5	3.1	2.0	0.4	1.0	12436.39	91.6%	88.5%	95.4%	21.14	0.0034	0.15
37	93.2	3.6	2.0	0.3	1.0	12616.20	91.7%	87.0%	95.5%	20.56	0.0041	0.17
38	93.4	3.2	1.9	0.5	1.0	12795.13	92.0%	88.1%	95.6%	20.20	0.0041	0.17
39	93.4	3.4	1.9	0.3	1.0	12975.26	92.1%	87.6%	95.6%	20.23	0.0036	0.15
40	93.7	3.1	1.8	0.4	1.0	13154.67	92.3%	88.7%	95.5%	19.45	0.0037	0.14
41	93.5	3.1	1.9	0.4	1.0	13334.98	91.9%	88.5%	95.4%	19.41	0.0037	0.14
42	93.7	3.1	1.9	0.3	1.0	13514.66	92.0%	88.6%	95.5%	18.71	0.0037	0.14
43	93.6	3.1	1.9	0.3	1.0	13695.04	91.8%	88.5%	95.4%	18.73	0.0036	0.14
44	93.6	3.1	2.0	0.3	1.0	13874.54	91.8%	88.6%	95.4%	18.80	0.0037	0.14
45	93.5	3.2	1.9	0.4	1.0	14054.02	92.0%	88.1%	95.5%	18.17	0.0037	0.13


Average Reaction Efficiencies *CSMP C3022-44-31 & Engelhard Escat 326
Average Reaction Efficiencies
*CSMP C3022-44-31 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0 5 10 15 20 25 30 35 40 45 50
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *CSMP C3022-44-31 & Engelhard Escat 326
Average Reformate Composition
*CSMP C3022-44-31 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0 5 10 15 20 25 30 35 40 45 50
Cycle
CH4
CO
N2
CO2
H2

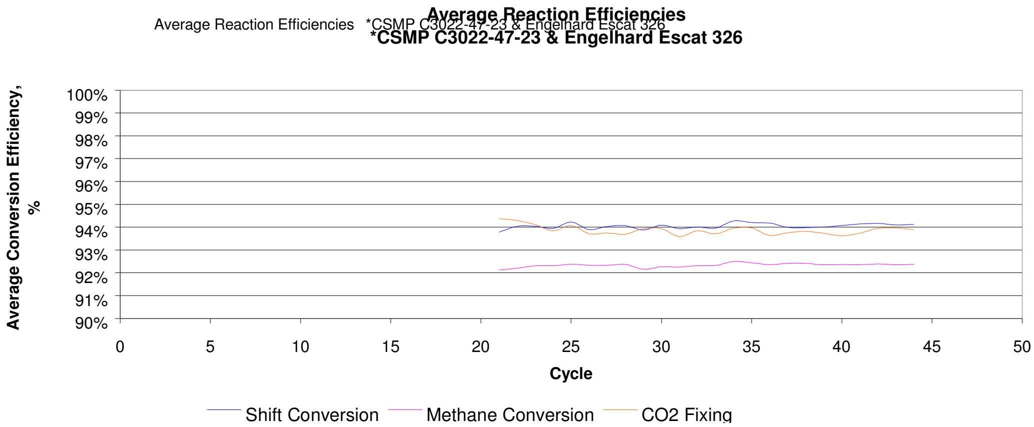

gCO2 Sorbed per g Sorbent *CSMP C3022-44-31 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*CSMP C3022-44-31 & Engelhard Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0 5 10 15 20 25 30 35 40 45 50
Cycle

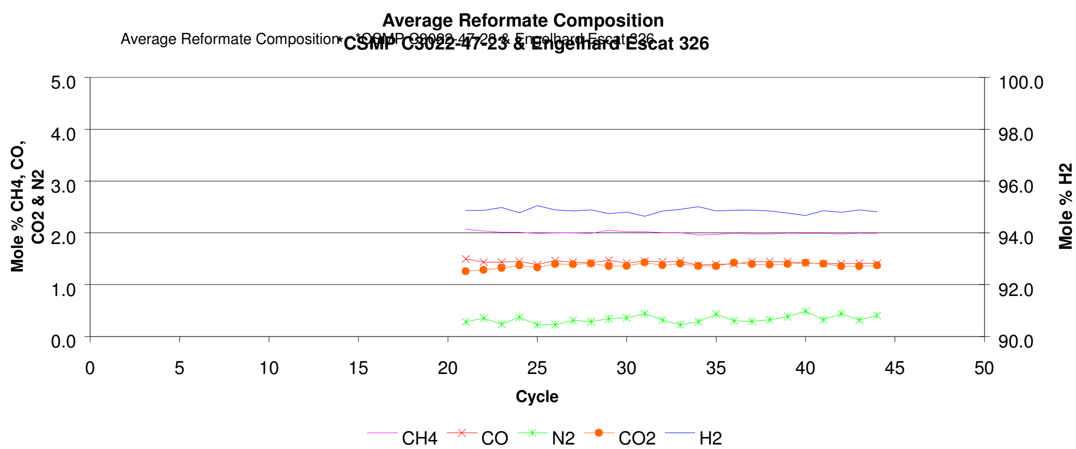
CO_2 Sorption Catalyst	*CSMP C3022-47-23
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/MgO(59:41)
Binder	15%Al203
Batch No.	HCM1781177E
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750 C

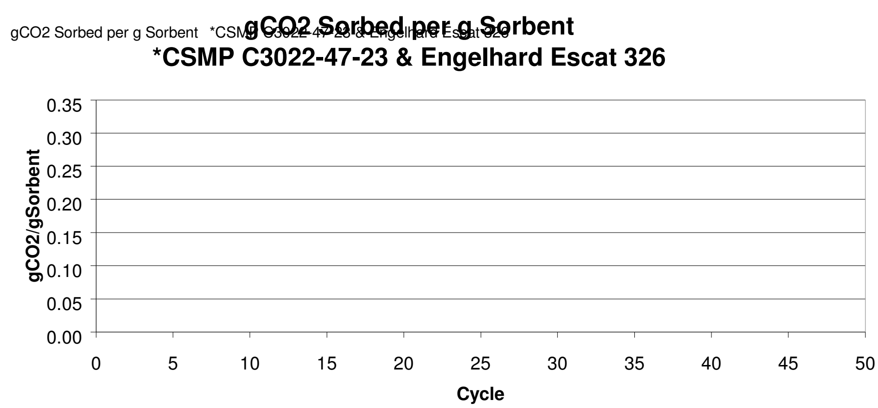
Wt. CO2 extrudate, g	24.7
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	29.2
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	Mass Spec sampling error cycles 1 - 20											
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21	94.9	2.1	1.5	0.3	1.3	34743.63	93.8%	92.1%	94.4%	25.94	0.0042	0.22
22	94.9	2.0	1.4	0.4	1.3	34952.43	94.0%	92.2%	94.3%	25.27	0.0042	0.21
23	95.0	2.0	1.4	0.2	1.3	35162.41	94.0%	92.3%	94.1%	24.77	0.0042	0.21
24	94.8	2.0	1.5	0.4	1.4	35371.99	93.9%	92.3%	93.8%	25.39	0.0042	0.21
25	95.0	2.0	1.4	0.2	1.3	35580.99	94.2%	92.4%	94.1%	23.97	0.0042	0.20
26	94.9	2.0	1.5	0.2	1.4	35791.39	93.9%	92.3%	93.7%	23.92	0.0042	0.20
27	94.8	2.0	1.4	0.3	1.4	36000.37	94.0%	92.3%	93.7%	23.92	0.0042	0.20
28	94.9	2.0	1.4	0.3	1.4	36210.06	94.1%	92.4%	93.7%	23.22	0.0042	0.20
29	94.7	2.0	1.5	0.3	1.4	41967.92	93.9%	92.2%	93.9%	22.99	0.0042	0.19
30	94.8	2.0	1.4	0.4	1.4	42176.63	94.1%	92.3%	93.9%	21.69	0.0042	0.18
31	94.6	2.0	1.5	0.4	1.4	42386.67	93.9%	92.3%	93.6%	22.56	0.0042	0.19
32	94.8	2.0	1.4	0.3	1.4	42596.48	94.0%	92.3%	93.8%	21.19	0.0042	0.18
33	94.9	2.0	1.5	0.2	1.4	42806.26	94.0%	92.3%	93.7%	21.08	0.0042	0.18
34	95.0	2.0	1.4	0.3	1.4	43015.34	94.3%	92.5%	94.0%	20.41	0.0042	0.17
35	94.8	2.0	1.4	0.4	1.4	43224.94	94.2%	92.4%	94.0%	20.40	0.0042	0.17
36	94.9	2.0	1.4	0.3	1.4	43435.11	94.2%	92.4%	93.6%	20.19	0.0042	0.17
37	94.9	2.0	1.4	0.3	1.4	43644.81	94.0%	92.4%	93.8%	19.51	0.0042	0.16
38	94.8	2.0	1.4	0.3	1.4	43854.12	94.0%	92.4%	93.8%	19.67	0.0042	0.17
39	94.8	2.0	1.4	0.4	1.4	44064.25	94.0%	92.3%	93.7%	19.60	0.0042	0.17
40	94.7	2.0	1.4	0.5	1.4	44274.18	94.1%	92.4%	93.6%	19.59	0.0042	0.17
41	94.9	2.0	1.4	0.3	1.4	44483.66	94.1%	92.4%	93.7%	18.91	0.0042	0.16
42	94.8	2.0	1.4	0.4	1.4	44693.59	94.2%	92.4%	93.9%	18.91	0.0042	0.16
43	94.9	2.0	1.4	0.3	1.4	44903.34	94.1%	92.4%	94.0%	18.13	0.0042	0.15
44	94.8	2.0	1.4	0.4	1.4	45112.98	94.1%	92.4%	93.9%	18.22	0.0042	0.15
	94.9	2.0	1.4	0.3	1.4	45323.49	94.0%	92.3%	93.8%	17.41	0.0042	0.15
	94.8	2.0	1.5	0.3	1.4	45533.14	93.8%	92.4%	93.8%	17.52	0.0042	0.15
	94.9	2.0	1.4	0.3	1.4	45742.69	94.1%	92.4%	93.8%	17.49	0.0042	0.15
	94.9	2.0	1.4	0.3	1.4	45952.48	94.0%	92.4%	93.7%	17.48	0.0042	0.15
	94.7	2.0	1.4	0.4	1.4	46162.95	94.0%	92.4%	93.7%	18.25	0.0042	0.15
	94.8	2.0	1.4	0.3	1.4	46372.58	94.0%	92.4%	93.7%	16.80	0.0042	0.14


Average Reaction Efficiencies *CSMP C3022-47-23 & Engelhard Escat 326
Average Reaction Efficiencies
*CSMP C3022-47-23 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
99%
98%
97%
96%
95%
94%
93%
92%
91%
90%
0 5 10 15 20 25 30 35 40 45 50
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *CSMP C3022-47-23 & Engelhard Escat 326
Average Reformate Composition
*CSMP C3022-47-23 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0 5 10 15 20 25 30 35 40 45 50
Cycle
CH4
CO
N2
CO2
H2

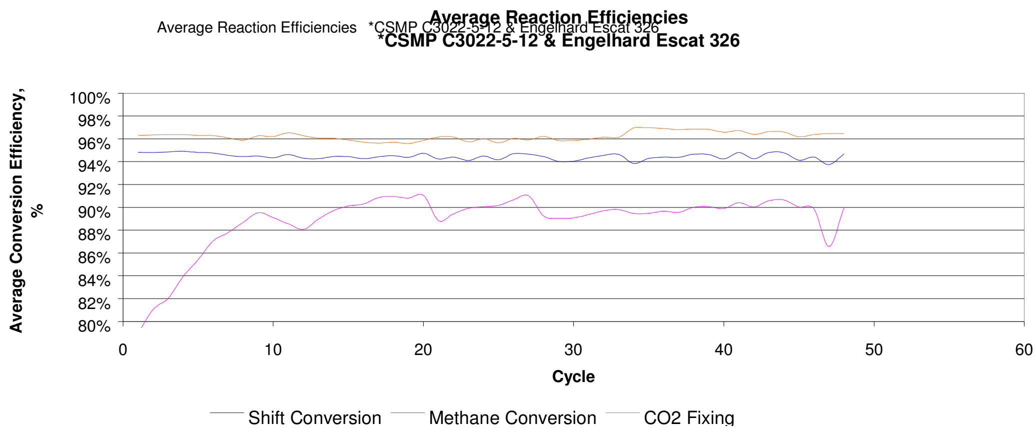

gCO2 Sorbed per g Sorbent *CSMP C3022-47-23 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*CSMP C3022-47-23 & Engelhard Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0 5 10 15 20 25 30 35 40 45 50
Cycle

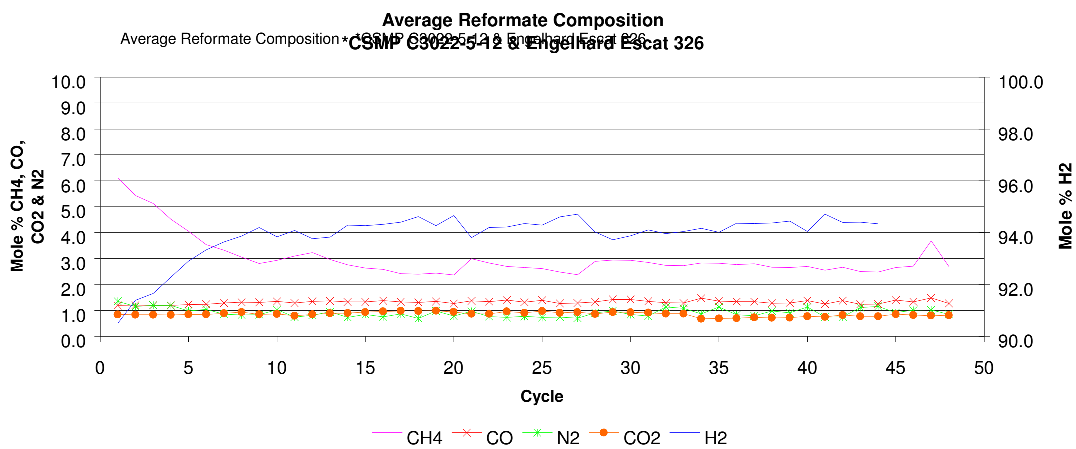
CO_2 Sorption Catalyst	*CSMP C3022-5-12
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/MgO (55:45)
Binder	15%Al203
Batch No.	HCM178165E
Extruded by	RTC
Oven Atmosphere	Air
Calcined, C	750 C

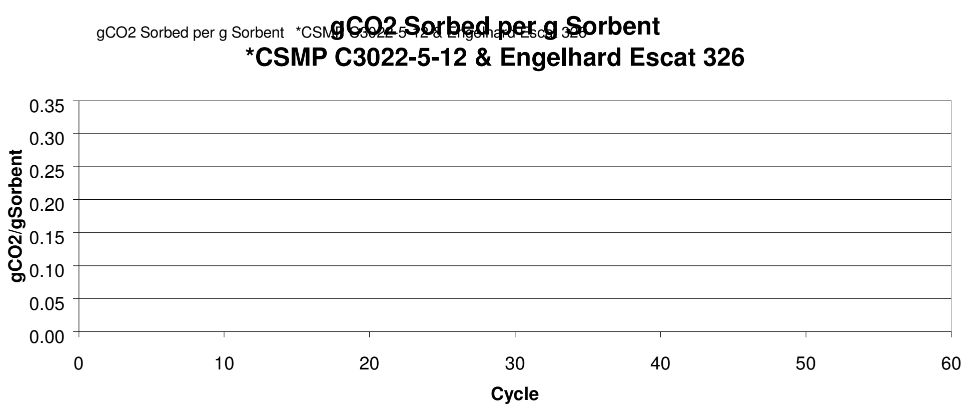
Wt. CO2 extrudate, g	26.0
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	24.1
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1.0

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Cycle Time	S	gCO2 / gSorb
1	90.5	6.1	1.2	1.3	0.8	1468.23	94.8%	79.0%	96.3%	14.25	0.0036	0.05
2	91.4	5.4	1.2	1.1	0.8	1654.37	94.8%	81.0%	96.3%	26.86	0.0037	0.10
3	91.6	5.1	1.2	1.2	0.8	1838.11	94.9%	82.0%	96.4%	37.51	0.0038	0.14
4	92.3	4.5	1.2	1.2	0.8	2018.95	94.9%	83.9%	96.4%	38.90	0.0039	0.15
5	92.9	4.1	1.2	1.0	0.8	2198.85	94.8%	85.4%	96.3%	38.94	0.0039	0.15
6	93.3	3.5	1.2	1.0	0.8	2377.99	94.8%	87.1%	96.3%	37.48	0.0040	0.15
7	93.6	3.3	1.3	0.9	0.9	2558.03	94.6%	87.8%	96.1%	37.55	0.0040	0.15
8	93.9	3.1	1.3	0.8	0.9	2737.97	94.4%	88.7%	95.9%	35.99	0.0041	0.15
9	94.2	2.8	1.3	0.8	0.8	2916.38	94.5%	89.5%	96.3%	34.50	0.0041	0.14
10	93.8	2.9	1.3	1.0	0.9	3096.16	94.3%	89.1%	96.2%	34.28	0.0041	0.14
11	94.1	3.1	1.3	0.7	0.8	275.50	94.6%	88.6%	96.5%	34.30	0.0041	0.14
12	93.8	3.2	1.3	0.8	0.8	453.84	94.3%	88.1%	96.3%	31.20	0.0040	0.13
13	93.8	3.0	1.4	0.9	0.9	633.18	94.3%	89.0%	96.1%	31.58	0.0041	0.13
14	94.3	2.7	1.3	0.7	0.9	812.97	94.5%	89.7%	96.1%	28.70	0.0041	0.12
15	94.3	2.6	1.3	0.8	0.9	992.79	94.5%	90.1%	95.9%	28.76	0.0041	0.12
16	94.3	2.6	1.4	0.7	1.0	1172.74	94.3%	90.3%	95.7%	28.84	0.0041	0.12
17	94.4	2.4	1.3	0.9	1.0	1352.50	94.4%	90.9%	95.6%	28.97	0.0041	0.12
18	94.6	2.4	1.3	0.7	1.0	1532.16	94.5%	91.0%	95.7%	27.31	0.0042	0.11
19	94.3	2.4	1.3	1.0	1.0	1712.37	94.4%	90.8%	95.6%	28.93	0.0041	0.12
20	94.7	2.4	1.3	0.8	0.9	1891.27	94.7%	91.0%	95.9%	26.80	0.0042	0.11
21	93.8	3.0	1.4	1.0	0.9	2071.90	94.2%	88.9%	96.2%	27.14	0.0041	0.11
22	94.2	2.8	1.3	0.8	0.9	2251.46	94.4%	89.4%	96.2%	25.42	0.0041	0.10
23	94.2	2.7	1.4	0.7	1.0	2432.31	94.1%	89.9%	95.7%	25.38	0.0041	0.10
24	94.4	2.6	1.3	0.8	0.9	2611.14	94.5%	90.1%	96.0%	25.30	0.0041	0.10
25	94.3	2.6	1.4	0.7	1.0	2791.95	94.2%	90.2%	95.7%	25.34	0.0041	0.10
26	94.6	2.5	1.3	0.7	0.9	2971.24	94.7%	90.7%	96.0%	23.50	0.0042	0.10
27	94.7	2.4	1.3	0.7	0.9	3151.13	94.7%	91.0%	95.9%	23.00	0.0042	0.10
28	94.0	2.9	1.3	0.9	0.9	3330.67	94.5%	89.2%	96.2%	23.12	0.0041	0.09
29	93.7	2.9	1.4	1.0	0.9	3510.84	94.0%	89.0%	95.9%	25.53	0.0041	0.10
30	93.9	2.9	1.4	0.8	0.9	3691.24	94.0%	89.1%	95.9%	23.43	0.0041	0.10
31	94.1	2.8	1.3	0.8	0.9	3870.60	94.3%	89.4%	96.0%	23.46	0.0041	0.10
32	94.0	2.7	1.3	1.1	0.9	4049.95	94.6%	89.7%	96.2%	23.50	0.0041	0.10
33	94.0	2.7	1.3	1.1	0.9	4229.51	94.6%	89.8%	96.1%	23.46	0.0041	0.10
34	94.2	2.8	1.5	0.9	0.7	160.58	93.8%	89.5%	97.0%	24.69	0.0041	0.10
35	94.0	2.8	1.4	1.1	0.7	339.14	94.3%	89.5%	97.0%	24.80	0.0041	0.10
36	94.4	2.8	1.3	0.8	0.7	519.75	94.4%	89.7%	96.9%	22.95	0.0041	0.10
37	94.3	2.8	1.3	0.8	0.7	699.56	94.4%	89.6%	96.8%	22.93	0.0041	0.09
38	94.4	2.7	1.3	1.0	0.7	879.07	94.7%	90.0%	96.9%	22.86	0.0042	0.10
39	94.4	2.6	1.3	0.9	0.7	1058.89	94.6%	90.1%	96.8%	22.97	0.0042	0.10
40	94.0	2.7	1.4	1.1	0.8	1239.54	94.2%	89.9%	96.6%	24.62	0.0041	0.10
41	94.7	2.5	1.2	0.7	0.7	1418.85	94.8%	90.4%	96.7%	21.63	0.0042	0.09
42	94.4	2.7	1.4	0.7	0.8	1600.06	94.3%	90.0%	96.4%	22.44	0.0041	0.09
43	94.4	2.5	1.2	1.1	0.8	1778.78	94.8%	90.6%	96.6%	22.55	0.0042	0.09
44	94.3	2.5	1.2	1.2	0.8	1958.67	94.8%	90.7%	96.6%	23.39	0.0042	0.10
45	94.2	2.7	1.4	0.9	0.9	2139.95	94.1%	90.0%	96.2%	23.44	0.0041	0.10
46	94.1	2.7	1.3	1.0	0.8	2319.13	94.4%	89.9%	96.4%	23.49	0.0041	0.10
47	93.0	3.7	1.5	1.0	0.8	2499.40	93.7%	86.6%	96.5%	21.27	0.0040	0.08
48	94.4	2.7	1.3	0.8	0.8	2678.65	94.7%	89.9%	96.5%	21.26	0.0041	0.09


Average Reaction Efficiencies *CSMP C3022-5-12 & Engelhard Escat 326
Average Reaction Efficiencies
*CSMP C3022-5-12 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *CSMP C3022-5-12 & Engelhard Escat 326
Average Reformate Composition
*CSMP C3022-5-12 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0
5
10
15
20
25
30
35
40
45
50
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent *CSMP C3022-5-12 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*CSMP C3022-5-12 & Engelhard Escat 326
gCO2/gSorbent
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
Cycle

APPENDIX F

CO_2 Sorption Catalyst Reforming Catalyst	ECM 255003 Engelhard Escat 326 (0.5%Rh on Alumina)	ECM 255008 Engelhard Escat 326 (0.5%Rh on Alumina)	ECM 255019 Engelhard Escat 326 (0.5%Rh on Alumina)	ECM 255021 Engelhard Escat 326 (0.5%Rh on Alumina)	ECM 255022 Engelhard Escat 326 (0.5%Rh on Alumina)	*ECM 255029 Engelhard Escat 326 (0.5%Rh on Alumina)
Composition CO_2 sorb	CaO (100)	CaO/MgO (80/20)	CaO/Al2O3 (95/5)	CaO/Al2O3 (90/10)	CaO/Al2O3 (90/10)	*CaO/Al203 (95/5)
Binder	15%Al203	15%Al203	15%Al203	10%Al203	15%Al203	15%Al203
Batch No.	Not Available	HCM178177E + HCM178178A	PCB953401A-1	PCB954103A-1	PCB954103A-1	PCB952502A-2
Extruded by	CSMP	CSMP	CSMP	CSMP	CSMP	CSMP
Oven Atmosphere	Air	Air	Air	Air	Air	Air
Calcined, °C	750	750	750	750	750	750
Wt. CO2 extrudate, g	26.16	24.23	24.91	19.63	19.99	24.98
Vol. CO2 extrudate, cc	32.5	32.5	32.5	32.5	32.5	32.5
Density CO2, g/cc	0.8	0.7	0.8	0.6	0.6	0.8
Wt. SMR Cat., g	4.5	4.5	4.5	4.5	4.5	4.5
Vol. SMR Cat., cc	7.5	7.5	7.5	7.5	7.5	7.5
Density SMR, g/cc	0.6	0.6	0.6	0.6	0.6	0.6
Total Bed Wt., g	30.66	28.73	29.41	24.13	24.49	29.48
Total Bed Vol., ml	40.0	40.0	40.0	40.0	40.0	40.0
Reactor	R1	R1	R2	R2	R2	R1
S/C	3	3	3	3	3	3
GHSV, hr-1	390	390	390	390	390	390
Reforming, °C	600	600	600	600	600	600
Calcination, °C	800	800	800	800	800	800
Pressure, atm.	1	1	1	1	1	1
Date loaded	2/24/2005	5/9/2005	2/24/2005	1/10/2005	1/24/2005	3/28/2005
Date unloaded	3/3/2005	5/19/2005	3/2/2005	1/14/2005	1/28/2005	4/11/2005
Sample	Extrudate	Extrudate	Extrudate	Extrudate	Extrudate	Extrudate
Post Run Description	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis
***Large Batch Extrusion**						

CO_2 Sorption Catalyst Reforming Catalyst	*ECM255036 Engelhard Escat 326 (0.5%Rh on Alumina)	*ECM255036 Engelhard Escat 326 (0.5%Rh on Alumina)	ECM255061C300 Engelhard Escat 326 (0.5%Rh on Alumina)	ECM255061C500 Engelhard Escat 326 (0.5%Rh on Alumina)	ECM255061C750 Engelhard Escat 326 (0.5%Rh on Alumina)	ECM255061C800 Engelhard Escat 326 (0.5%Rh on Alumina)
Composition CO_2 sorb	*CaO/Al203 (90/10)	*CaO/Al203 (90/10)	*CaO/Al203 (90/10)	*CaO/Al203 (90/10)	*CaO/Al203 (90/10)	CaO/Al203 (90/10)
Binder	15%Al203	15%Al203	15%Al203	15%Al203	15%Al203	15%Al203
Batch No.	ECM255032 + ECM255033	ECM255032 + ECM255033	PCB954103A-1(HCB198078B +	PCB954103A-1(HCB198078B +	PCB954103A-1(HCB198078B +	PCB954103A-1(HCB198078B +
Extruded by	CSMP	CSMP	CSMP	CSMP	CSMP	CSMP
Oven Atmosphere	Air	Air	Air	Air	Air	Air
Calcined, °C	750	750	300	500	750	800
Wt. CO2 extrudate, g	27	30	32.16	31.85	27.96	24.82
Vol. CO2 extrudate, cc	32.5	32.5	32.5	32.5	32.5	32.5
Density CO2, g/cc	0.8	0.9	1.0	1.0	0.9	0.8
Wt. SMR Cat., g	4.5	4.5	4.5	4.5	4.5	4.5
Vol. SMR Cat., cc	7.5	7.5	7.5	7.5	7.5	7.5
Density SMR, g/cc	0.6	0.6	0.6	0.6	0.6	0.6
Total Bed Wt., g	31.5	34.5	36.66	36.35	32.46	29.32
Total Bed Vol., ml	40.0	40.0	40.0	40.0	40.0	40.0
Reactor	R1	R2	R1	R2	R1	R1
S/C	3	3	3	3	3	3
GHSV, hr-1	390	390	390	390	390	390
Reforming, °C	600	600	600	600	600	600
Calcination, °C	800	800	800	800	800	800
Pressure, atm.	1	1	1	1	1	1
Date loaded	4/26/2005	5/9/2005	5/19/2005	6/8/2005	6/21/2005	7/5/2005
Date unloaded	5/8/2005	5/22/2005	5/29/2005	6/15/2005	Heater Failed	7/15/2005
Sample	Extrudate	Extrudate	Extrudate	Extrudate	Extrudate	Extrudate
Post Run Description	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis
***Large Batch Extrusion**						

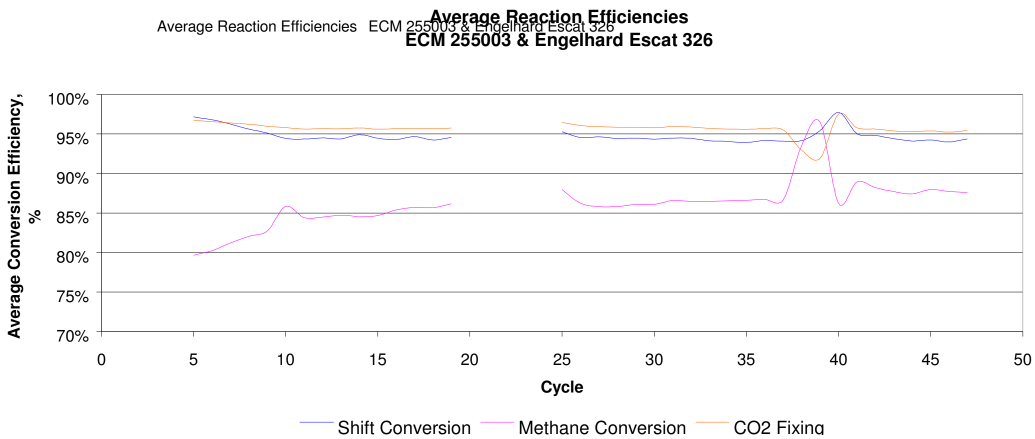
CO_2 Sorption Catalyst Reforming Catalyst	ECM259002-2C Engelhard Escat 326 (0.5%Rh on Alumina)	ECM259-011C Engelhard Escat 326 (0.5%Rh on Alumina)	*ECM259012C Engelhard Escat 326 (0.5%Rh on Alumina)	*ECM259013C Engelhard SRXX	*ECM259013C Engelhard Escat 326 (0.5%Rh on Alumina)	*ECM259018C800 Engelhard Escat 326 (0.5%Rh on Alumina)
Composition CO_2 sorb	CaO/Al203 (90/10)	CaO/Al203 (90/10)	CaO/Al203 (90/10)	CaO/Al2O3 (90/10)	CaO/Al2O3 (90/10)	CaO/Al2O3 (90/10)
Binder	15%Al203	15%Al203	15%Al203	15%Al203	15%Al203	15%Al203
Batch No.	PCB290040C (HCB203020A)	Not Available	ECM259007-009	HCB326030B	HCB326030B	HCB203032A (030A+031A)
Extruded by	CSMP	CSMP	CSMP	CSMP	CSMP	CSMP
Oven Atmosphere	N2	N2	Air	Air	Air	N2
Calcined, °C	750	750	750	750	750	800
Wt. CO2 extrudate, g	27.73	26.13	26.57	24.75	24.72	23.04
Vol. CO2 extrudate, cc	32.5	32.5	32.5	32.5	32.5	32.5
Density CO2, g/cc	0.9	0.8	0.8	0.8	0.8	0.7
Wt. SMR Cat., g	4.5	4.5	4.5	4.5	4.5	4.5
Vol. SMR Cat., cc	7.5	7.5	7.5	7.5	7.5	7.5
Density SMR, g/cc	0.6	0.6	0.6	0.6	0.6	0.6
Total Bed Wt., g	32.23	30.63	31.07	29.25	29.22	27.54
Total Bed Vol., ml	40.0	40.0	40.0	40.0	40.0	40.0
Reactor	R1	R2	R2	R1	R2	R1
S/C	3	3	3	3	3	3
GHSV, hr-1	390	390	390	390	390	390
Reforming, °C	600	600	600	600	600	600
Calcination, °C	800	800	800	800	800	800
Pressure, atm.	1	1	1	1	1	1
Date loaded	6/8/2005	6/21/2005	7/5/2005	8/4/2005	8/4/2005	12/2/2005
Date unloaded	6/20/2005	6/30/2005	7/15/2005	8/22/2005	8/22/2005	12/12/2005
Sample	Extrudate	Extrudate	Extrudate	Extrudate	Extrudate	Extrudate
Post Run Description	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis	See Sieve Analysis
***Large Batch Extrusion**						

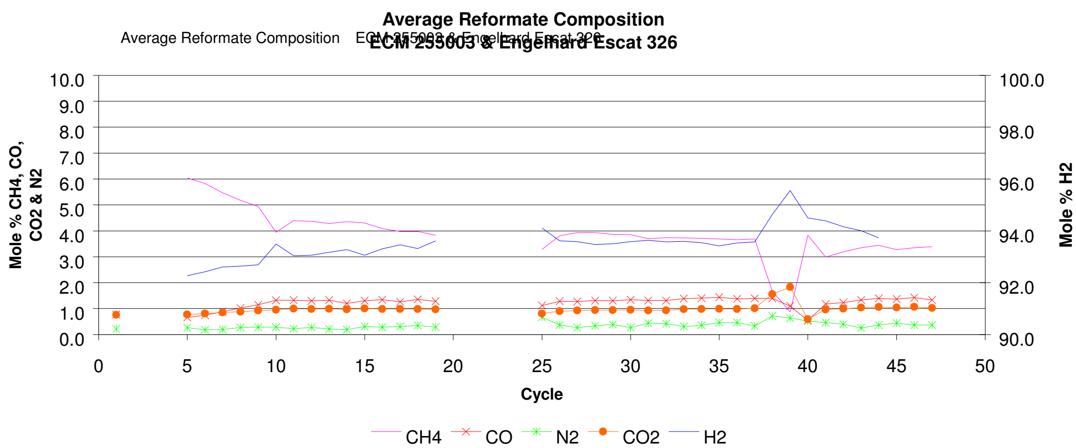
CO_2 Sorption Catalyst	ECM 255003
Reforming Catalyst: 0.5% rhodium o	Engelhard Escat 326
Composition CO_2 sorb	CaO (100)
Binder	15%Al203
Batch No.	Not Available
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

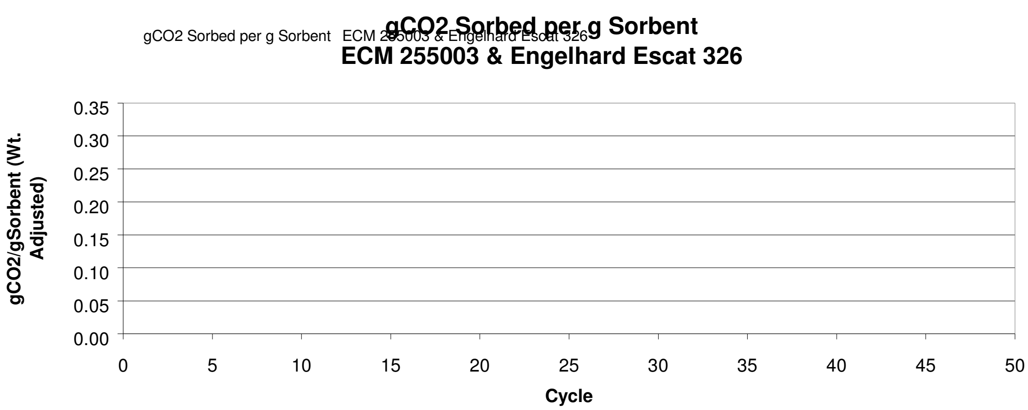
Wt. CO2 extrudate, g	26.16
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	30.66
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	95.3	2.9	0.8	0.2	0.8	233.11	96.8%	89.3%	96.8%	29.46	0.0041	0.24
2												
3												
4												
5	92.3	6.0	0.7	0.3	0.8	949.71	97.2%	79.7%	96.7%	27.31	0.0037	0.20
6	92.4	5.8	0.7	0.2	0.8	1132.46	96.8%	80.2%	96.6%	29.48	0.0037	0.22
7	92.6	5.5	0.9	0.2	0.8	1312.94	96.2%	81.2%	96.4%	29.41	0.0037	0.22
8	92.6	5.2	1.0	0.3	0.9	1492.32	95.6%	82.1%	96.2%	29.18	0.0037	0.22
9	92.7	4.9	1.1	0.3	0.9	1671.74	95.1%	82.7%	96.0%	28.57	0.0037	0.21
10	93.5	3.9	1.3	0.3	1.0	1889.58	94.4%	85.8%	95.8%	29.12	0.0038	0.22
11	93.0	4.4	1.3	0.2	1.0	2066.62	94.4%	84.4%	95.6%	26.53	0.0037	0.20
12	93.1	4.4	1.3	0.3	1.0	2243.97	94.5%	84.5%	95.7%	23.55	0.0037	0.18
13	93.2	4.3	1.3	0.2	1.0	2422.06	94.4%	84.7%	95.7%	21.41	0.0037	0.16
14	93.3	4.4	1.2	0.2	1.0	2600.39	94.9%	84.5%	95.8%	19.33	0.0038	0.15
15	93.1	4.3	1.3	0.3	1.0	2780.32	94.5%	84.7%	95.6%	20.51	0.0037	0.15
16	93.3	4.1	1.3	0.3	1.0	2959.09	94.3%	85.4%	95.7%	18.38	0.0038	0.14
17	93.5	4.0	1.3	0.3	1.0	3137.86	94.6%	85.7%	95.7%	17.66	0.0038	0.13
18	93.3	4.0	1.4	0.4	1.0	3318.06	94.2%	85.7%	95.7%	17.69	0.0038	0.13
19	93.6	3.8	1.3	0.3	1.0	3496.49	94.6%	86.2%	95.7%	16.08	0.0038	0.12
20												
21												
22												
23												
24												
25	94.1	3.3	1.1	0.7	0.8	5897.01	95.3%	88.0%	96.5%	16.88	0.0040	0.13
26	93.6	3.8	1.3	0.4	0.9	6080.71	94.6%	86.2%	96.1%	20.41	0.0038	0.16
27	93.6	3.9	1.3	0.3	0.9	6259.70	94.6%	85.8%	95.9%	19.20	0.0038	0.15
28	93.5	3.9	1.3	0.3	0.9	6439.14	94.4%	85.8%	95.9%	18.37	0.0038	0.14
29	93.5	3.9	1.3	0.4	0.9	6617.87	94.5%	86.1%	95.9%	18.36	0.0038	0.14
30	93.6	3.8	1.3	0.3	1.0	6797.80	94.3%	86.1%	95.8%	16.78	0.0038	0.13
31	93.6	3.7	1.3	0.4	0.9	6976.26	94.5%	86.6%	95.9%	16.86	0.0038	0.13
32	93.6	3.7	1.3	0.4	0.9	7156.03	94.4%	86.5%	95.9%	15.43	0.0038	0.12
33	93.6	3.7	1.4	0.3	1.0	7336.29	94.1%	86.5%	95.7%	16.05	0.0038	0.12
34	93.5	3.7	1.4	0.4	1.0	7515.75	94.1%	86.6%	95.6%	15.36	0.0038	0.12
35	93.4	3.7	1.4	0.5	1.0	7695.23	93.9%	86.6%	95.6%	15.45	0.0038	0.12
36	93.5	3.7	1.4	0.5	1.0	7874.68	94.2%	86.7%	95.7%	14.75	0.0038	0.11
37	93.6	3.7	1.4	0.3	1.0	8054.96	94.1%	86.6%	95.5%	14.78	0.0038	0.11
38	94.6	1.7	1.4	0.7	1.6	8231.74	94.2%	93.5%	93.0%	12.52	0.0040	0.10
39	95.6	0.9	1.1	0.6	1.8	8405.42	95.4%	96.5%	91.9%	5.91	0.0041	0.05
40	94.5	3.8	0.5	0.5	0.6	8599.41	97.7%	86.2%	97.5%	15.42	0.0040	0.12
41	94.4	3.0	1.2	0.5	1.0	8832.53	95.0%	88.9%	95.8%	23.36	0.0040	0.18
42	94.2	3.2	1.2	0.4	1.0	9011.69	94.8%	88.2%	95.6%	22.69	0.0039	0.18
43	94.0	3.4	1.3	0.3	1.0	9192.57	94.4%	87.7%	95.4%	22.00	0.0039	0.17
44	93.7	3.4	1.4	0.4	1.1	9371.92	94.1%	87.4%	95.3%	22.71	0.0038	0.17
45	93.9	3.3	1.4	0.4	1.0	9550.59	94.2%	88.0%	95.4%	21.23	0.0039	0.16
46	93.8	3.3	1.4	0.4	1.1	9730.71	94.0%	87.7%	95.2%	21.23	0.0038	0.16
47	93.9	3.4	1.3	0.4	1.0	9909.46	94.4%	87.6%	95.5%	19.67	0.0039	0.15


Average Reaction Efficiencies ECM 255003 & Engelhard Escat 326
Average Reaction Efficiencies
ECM 255003 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
0
5
10
15
20
25
30
35
40
45
50
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM 255003 & Engelhard Escat 326
Average Reformate Composition
ECM 255003 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
5
10
15
20
25
30
35
40
45
50
Cycle
CH4
CO
N2
CO2
H2

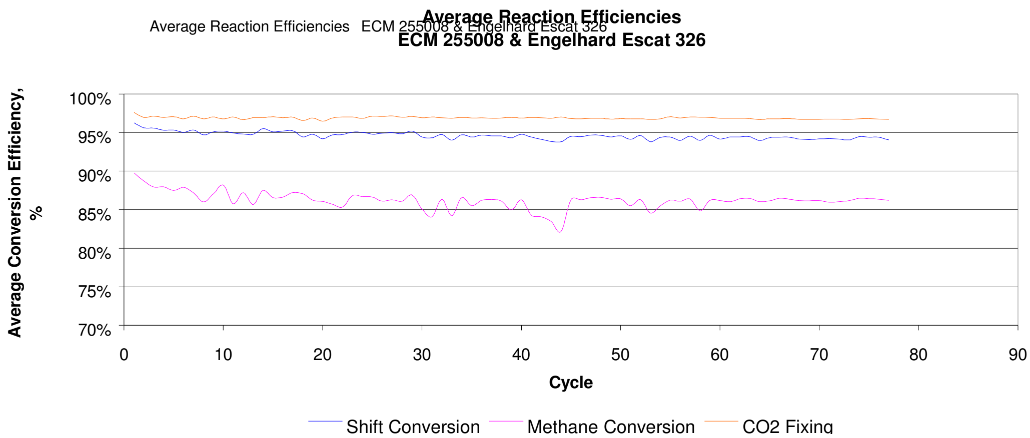

gCO2 Sorbed per g Sorbent ECM 255003 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM 255003 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
40
45
50
Cycle

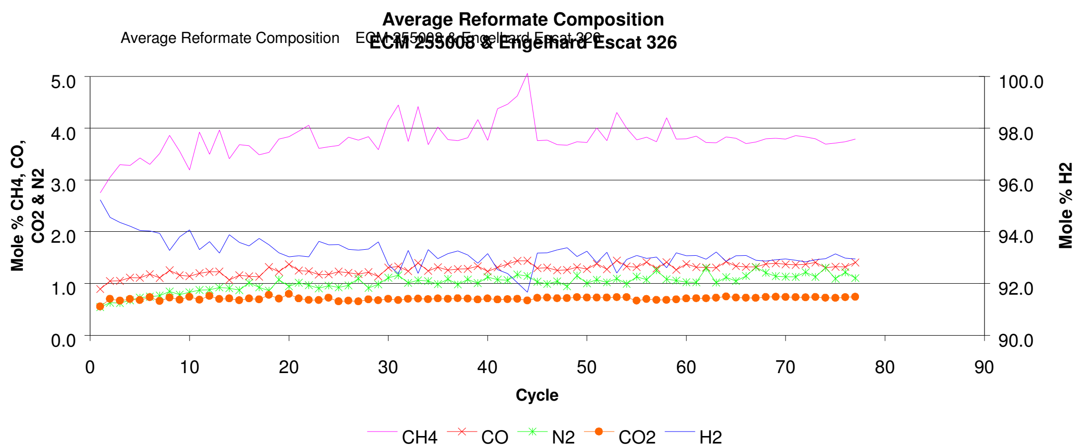
CO_2 Sorption Catalyst	ECM 255008
Reforming Catalyst: 0.5% rhodium on	Engelhard Escat 326
Composition CO_2 sorb	CaO/MgO (80/20)
Binder	15%Al203
Batch No.	HCM178177E + HCM178178A
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

Wt. CO2 extrudate, g	24.23
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.7
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	28.73
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	95.2	2.8	0.9	0.5	0.6	557.68	96.3%	89.8%	97.6%	25.17	0.0045	0.29
2	94.5	3.1	1.0	0.6	0.7	736.09	95.6%	88.7%	97.0%	23.47	0.0043	0.27
3	94.4	3.3	1.0	0.6	0.7	914.59	95.6%	87.9%	97.1%	21.92	0.0043	0.25
4	94.2	3.3	1.1	0.7	0.7	1093.38	95.3%	88.0%	97.0%	20.39	0.0043	0.23
5	94.1	3.4	1.1	0.7	0.7	1272.31	95.3%	87.5%	97.1%	20.16	0.0043	0.22
6	94.0	3.3	1.2	0.7	0.7	1451.70	95.0%	87.9%	96.8%	18.68	0.0043	0.21
7	93.9	3.5	1.1	0.8	0.7	1630.34	95.3%	87.2%	97.1%	17.99	0.0043	0.20
8	93.3	3.9	1.3	0.8	0.7	1810.77	94.7%	86.0%	96.8%	17.51	0.0042	0.19
9	93.8	3.6	1.2	0.8	0.7	1989.43	95.1%	87.0%	97.0%	16.97	0.0042	0.19
10	94.1	3.2	1.1	0.8	0.7	2168.13	95.2%	88.2%	96.8%	15.36	0.0043	0.17
11	93.3	3.9	1.2	0.9	0.7	2348.10	94.9%	85.8%	97.0%	15.79	0.0042	0.17
12	93.6	3.5	1.2	0.9	0.8	2527.97	94.8%	87.2%	96.7%	15.21	0.0042	0.17
13	93.2	4.0	1.2	0.9	0.7	2707.39	94.8%	85.7%	96.9%	15.32	0.0042	0.17
14	93.9	3.4	1.1	0.9	0.7	2886.01	95.5%	87.5%	96.9%	13.61	0.0043	0.15
15	93.6	3.7	1.2	0.9	0.7	3066.52	95.1%	86.6%	97.1%	13.67	0.0042	0.15
16	93.5	3.7	1.1	1.0	0.7	3245.66	95.2%	86.6%	96.9%	13.58	0.0042	0.15
17	93.7	3.5	1.1	0.9	0.7	3425.90	95.2%	87.2%	97.0%	12.66	0.0042	0.14
18	93.5	3.5	1.3	0.9	0.8	3607.59	94.4%	87.1%	96.6%	14.82	0.0042	0.16
19	93.2	3.8	1.2	1.1	0.7	3785.97	94.8%	86.2%	96.9%	13.78	0.0042	0.15
20	93.0	3.8	1.4	0.9	0.8	3967.27	94.2%	86.1%	96.5%	14.71	0.0041	0.16
21	93.1	3.9	1.2	1.0	0.7	4145.73	94.7%	85.7%	96.9%	13.09	0.0041	0.14
22	93.0	4.1	1.2	1.0	0.7	4324.80	94.7%	85.3%	97.0%	12.39	0.0041	0.13
23	93.6	3.6	1.2	0.9	0.7	4505.16	95.0%	86.8%	97.0%	12.03	0.0042	0.13
24	93.5	3.6	1.2	1.0	0.7	4684.53	95.0%	86.7%	96.8%	12.49	0.0042	0.14
25	93.5	3.7	1.2	0.9	0.7	4865.54	94.8%	86.6%	97.1%	12.42	0.0042	0.14
26	93.3	3.8	1.2	1.0	0.7	5044.65	94.9%	86.1%	97.1%	12.29	0.0042	0.13
27	93.3	3.8	1.2	1.1	0.7	5224.77	95.0%	86.3%	97.2%	12.40	0.0042	0.14
28	93.3	3.8	1.2	0.9	0.7	5404.36	94.8%	86.1%	97.0%	11.81	0.0042	0.13
29	93.6	3.6	1.1	1.0	0.7	5583.96	95.2%	86.9%	97.1%	11.19	0.0042	0.12
30	92.7	4.1	1.3	1.1	0.7	5764.62	94.4%	85.1%	96.9%	12.82	0.0041	0.14
31	92.4	4.5	1.3	1.2	0.7	5943.97	94.3%	84.1%	97.0%	11.58	0.0041	0.12
32	93.3	3.7	1.2	1.0	0.7	6124.28	94.7%	86.4%	96.9%	11.27	0.0042	0.12
33	92.4	4.4	1.4	1.1	0.7	6304.35	94.0%	84.2%	96.9%	11.40	0.0040	0.12
34	93.3	3.7	1.2	1.0	0.7	6483.77	94.7%	86.6%	96.9%	10.86	0.0042	0.12
35	93.0	4.0	1.3	1.0	0.7	6663.67	94.4%	85.5%	96.9%	10.86	0.0041	0.12
36	93.2	3.8	1.3	1.1	0.7	6843.49	94.7%	86.2%	96.9%	10.89	0.0042	0.12
37	93.3	3.8	1.3	1.0	0.7	7023.44	94.6%	86.3%	96.9%	10.84	0.0042	0.12
38	93.1	3.8	1.3	1.1	0.7	7203.42	94.5%	86.1%	96.9%	10.87	0.0042	0.12
39	92.8	4.2	1.3	1.0	0.7	7383.18	94.3%	85.0%	97.0%	10.77	0.0041	0.12
40	93.2	3.8	1.2	1.1	0.7	7562.70	94.8%	86.3%	96.9%	10.26	0.0042	0.11
41	92.5	4.4	1.3	1.1	0.7	7742.83	94.4%	84.3%	97.0%	10.30	0.0041	0.11
42	92.4	4.5	1.4	1.1	0.7	7923.01	94.1%	84.1%	96.9%	9.78	0.0040	0.10
43	92.0	4.6	1.4	1.2	0.7	8103.68	93.8%	83.5%	96.9%	10.21	0.0040	0.11
44	91.7	5.1	1.4	1.1	0.7	8283.16	93.8%	82.2%	97.0%	9.67	0.0039	0.10
45	93.2	3.8	1.3	1.0	0.7	8462.93	94.5%	86.3%	96.8%	9.80	0.0042	0.11
46	93.2	3.8	1.3	1.0	0.7	8642.75	94.5%	86.3%	96.8%	9.72	0.0042	0.11
47	93.3	3.7	1.3	1.0	0.7	8822.49	94.7%	86.6%	96.9%	9.25	0.0042	0.10
48	93.4	3.7	1.3	0.9	0.7	9002.28	94.7%	86.6%	96.9%	9.29	0.0042	0.10
49	93.0	3.7	1.3	1.2	0.7	9182.45	94.4%	86.3%	96.8%	9.74	0.0042	0.11
50	93.2	3.7	1.3	1.0	0.7	9362.03	94.6%	86.4%	96.8%	9.25	0.0042	0.10
51	92.8	4.0	1.4	1.1	0.7	9542.64	94.1%	85.5%	96.8%	9.71	0.0041	0.10
52	93.2	3.8	1.3	1.0	0.7	9721.66	94.6%	86.3%	96.8%	9.17	0.0042	0.10
53	92.4	4.3	1.4	1.1	0.7	9902.52	93.8%	84.6%	96.7%	9.39	0.0040	0.10
54	92.9	4.0	1.3	1.0	0.7	10082.22	94.4%	85.5%	96.8%	9.23	0.0041	0.10
55	93.1	3.8	1.3	1.1	0.7	10261.85	94.4%	86.2%	97.1%	9.24	0.0042	0.10
56	93.0	3.8	1.4	1.1	0.7	10442.63	94.0%	86.1%	96.9%	9.24	0.0041	0.10
57	93.0	3.7	1.3	1.3	0.7	10621.35	94.5%	86.4%	97.0%	9.19	0.0042	0.10
58	92.6	4.2	1.4	1.1	0.7	10802.68	94.0%	84.9%	97.0%	8.61	0.0041	0.09
59	93.2	3.8	1.3	1.1	0.7	10981.45	94.6%	86.2%	97.0%	8.70	0.0042	0.09
60	93.1	3.8	1.4	1.0	0.7	11162.21	94.2%	86.2%	96.9%	8.65	0.0041	0.09
61	93.1	3.8	1.3	1.0	0.7	11341.25	94.4%	86.0%	96.9%	8.63	0.0041	0.09
62	92.9	3.7	1.3	1.3	0.7	11521.08	94.4%	86.4%	96.9%	8.64	0.0042	0.09
63	93.2	3.7	1.3	1.0	0.7	11701.11	94.5%	86.4%	96.8%	8.14	0.0042	0.09
64	92.9	3.8	1.4	1.1	0.7	11881.68	94.0%	86.1%	96.7%	8.73	0.0041	0.09
65	93.1	3.8	1.3	1.0	0.7	12061.01	94.3%	86.2%	96.8%	8.21	0.0041	0.09
66	93.1	3.7	1.3	1.1	0.7	12240.98	94.4%	86.5%	96.8%	8.10	0.0042	0.09
67	92.9	3.7	1.3	1.3	0.7	12420.96	94.4%	86.4%	96.8%	8.12	0.0042	0.09
68	92.9	3.8	1.4	1.2	0.7	12601.08	94.1%	86.2%	96.7%	8.62	0.0041	0.09
69	92.9	3.8	1.4	1.1	0.7	12781.40	94.1%	86.1%	96.7%	8.12	0.0041	0.09
70	92.9	3.8	1.4	1.1	0.7	12960.95	94.2%	86.2%	96.7%	8.16	0.0041	0.09
71	92.9	3.9	1.4	1.1	0.7	13141.08	94.2%	86.0%	96.8%	7.55	0.0041	0.08
72	92.8	3.8	1.4	1.2	0.7	13320.66	94.2%	86.1%	96.8%	8.22	0.0041	0.09
73	92.9	3.8	1.4	1.1	0.7	13501.38	94.0%	86.2%	96.7%	8.10	0.0041	0.09
74	93.0	3.7	1.3	1.3	0.7	13680.32	94.5%	86.5%	96.8%	8.11	0.0042	0.09
75	93.1	3.7	1.3	1.1	0.7	13860.91	94.4%	86.4%	96.8%	7.64	0.0042	0.08
76	93.0	3.7	1.3	1.2	0.7	14040.41	94.4%	86.4%	96.8%	8.14	0.0042	0.09
77	93.0	3.8	1.4	1.1	0.7	14221.21	94.0%	86.2%	96.7%	8.19	0.0041	0.09


Average Reaction Efficiencies ECM 255008 & Engelhard Escat 326
Average Reaction Efficiencies
ECM 255008 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
0
10
20
30
40
50
60
70
80
90
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM 255008 & Engelhard Escat 326
Average Reformate Composition
ECM 255008 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0
10
20
30
40
50
60
70
80
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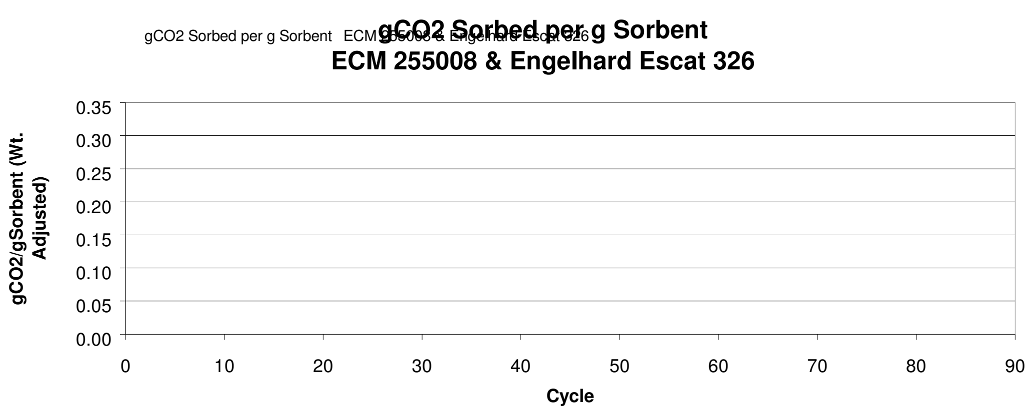
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent ECM 255008 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM 255008 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
90
Cycle

CO_2 Sorption Catalyst	ECM 255019
Reforming Catalyst: 0.5% rhodium on	Engelhard Escat 326
Composition CO_2 sorb	CaO/Al2O3 (95/5)
Binder	15%Al203
Batch No.	PCB953401A-1
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

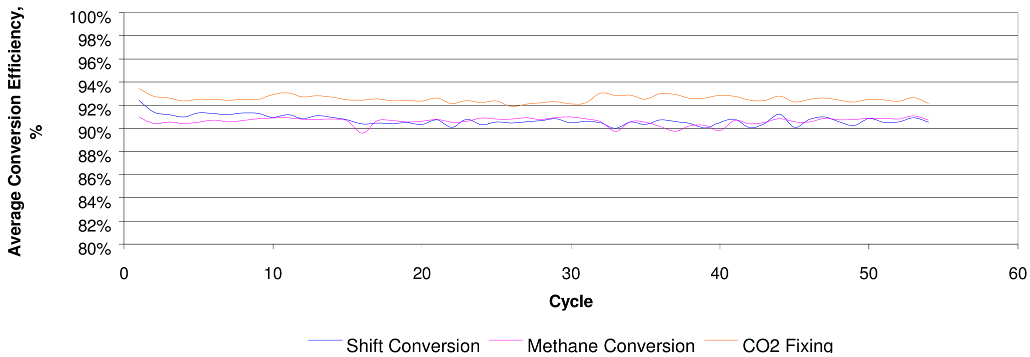
Wt. CO2 extrudate, g	24.91
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	29.41
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	94.1	2.4	1.8	0.2	1.4	233.13	92.4%	91.0%	93.4%	29.47	0.0040	0.25
2	93.7	2.5	2.0	0.1	1.6	411.22	91.4%	90.4%	92.8%	27.23	0.0039	0.22
3	93.6	2.5	2.1	0.2	1.6	588.20	91.2%	90.6%	92.6%	24.24	0.0039	0.20
4	93.4	2.5	2.2	0.2	1.6	766.77	91.0%	90.4%	92.4%	23.53	0.0039	0.19
5	93.6	2.5	2.1	0.2	1.6	945.32	91.3%	90.5%	92.5%	21.48	0.0039	0.18
6	93.6	2.5	2.1	0.2	1.6	1123.67	91.3%	90.7%	92.5%	20.68	0.0039	0.17
7	93.5	2.5	2.1	0.2	1.6	1303.40	91.2%	90.6%	92.4%	19.87	0.0039	0.16
8	93.6	2.5	2.1	0.3	1.6	1482.15	91.3%	90.7%	92.5%	19.00	0.0039	0.15
9	93.6	2.4	2.1	0.3	1.6	1661.53	91.3%	90.8%	92.5%	18.35	0.0039	0.15
10	93.5	2.4	2.2	0.4	1.5	1879.14	91.0%	90.9%	92.9%	18.67	0.0039	0.15
11	93.6	2.4	2.1	0.4	1.5	2057.81	91.2%	90.9%	93.1%	17.72	0.0040	0.15
12	93.5	2.4	2.2	0.3	1.6	2238.12	90.8%	90.8%	92.7%	17.69	0.0039	0.14
13	93.7	2.4	2.1	0.2	1.5	2417.67	91.1%	90.8%	92.8%	16.90	0.0039	0.14
14	93.6	2.4	2.2	0.2	1.6	2597.45	91.0%	90.8%	92.7%	16.38	0.0039	0.13
15	93.4	2.5	2.2	0.3	1.6	2776.70	90.7%	90.7%	92.5%	16.77	0.0039	0.14
16	93.0	2.8	2.3	0.3	1.6	2956.16	90.4%	89.6%	92.4%	15.43	0.0038	0.12
17	93.2	2.5	2.3	0.3	1.6	3135.68	90.5%	90.7%	92.6%	15.46	0.0039	0.12
18	93.3	2.5	2.3	0.3	1.6	3315.89	90.4%	90.7%	92.4%	15.50	0.0039	0.13
19	93.2	2.5	2.3	0.4	1.6	3495.79	90.5%	90.6%	92.4%	15.37	0.0039	0.12
20	93.3	2.5	2.3	0.3	1.6	3675.53	90.3%	90.6%	92.4%	14.82	0.0039	0.12
21	93.4	2.4	2.2	0.3	1.6	3854.80	90.7%	90.8%	92.6%	14.13	0.0039	0.11
22	93.2	2.5	2.4	0.3	1.7	4035.28	90.1%	90.5%	92.1%	14.00	0.0039	0.11
23	93.3	2.5	2.2	0.4	1.6	4214.35	90.8%	90.6%	92.4%	13.90	0.0039	0.11
24	93.1	2.4	2.3	0.5	1.7	4393.84	90.3%	90.9%	92.2%	13.88	0.0039	0.11
25	93.2	2.4	2.3	0.5	1.6	4573.70	90.6%	90.8%	92.4%	13.21	0.0039	0.11
26	93.0	2.4	2.3	0.6	1.7	4753.64	90.5%	90.8%	91.9%	13.94	0.0039	0.11
27	93.3	2.4	2.2	0.4	1.7	4933.66	90.6%	90.9%	92.1%	13.26	0.0039	0.11
28	93.3	2.4	2.2	0.3	1.7	5113.57	90.7%	90.8%	92.2%	12.44	0.0039	0.10
29	93.3	2.4	2.2	0.4	1.7	5292.59	90.8%	91.0%	92.3%	12.36	0.0039	0.10
30	93.3	2.4	2.3	0.4	1.7	5472.93	90.5%	91.0%	92.1%	12.47	0.0039	0.10
31	93.4	2.4	2.2	0.3	1.7	5652.80	90.6%	90.8%	92.2%	11.78	0.0039	0.10
32	93.3	2.5	2.3	0.5	1.5	5879.42	90.5%	90.6%	93.1%	12.55	0.0039	0.10
33	92.9	2.7	2.4	0.5	1.5	6059.53	90.0%	89.7%	92.8%	12.52	0.0038	0.10
34	93.3	2.5	2.3	0.4	1.5	6239.02	90.6%	90.6%	92.9%	11.94	0.0039	0.10
35	93.2	2.5	2.3	0.4	1.6	6419.29	90.3%	90.5%	92.5%	11.89	0.0039	0.10
36	93.1	2.6	2.2	0.6	1.5	6598.00	90.7%	90.2%	93.0%	11.81	0.0039	0.10
37	93.2	2.7	2.2	0.3	1.5	6778.86	90.6%	89.8%	92.9%	11.04	0.0039	0.09
38	93.3	2.6	2.3	0.2	1.6	6958.62	90.4%	90.2%	92.6%	11.10	0.0039	0.09
39	93.1	2.6	2.4	0.3	1.6	7138.45	90.0%	90.3%	92.6%	11.04	0.0039	0.09
40	93.1	2.7	2.3	0.3	1.5	7318.02	90.5%	89.8%	92.9%	10.99	0.0039	0.09
41	93.3	2.5	2.2	0.4	1.6	7497.46	90.8%	90.7%	92.8%	10.33	0.0039	0.08
42	93.0	2.5	2.4	0.4	1.6	7678.32	90.1%	90.4%	92.4%	10.32	0.0039	0.08
43	93.1	2.5	2.3	0.5	1.6	7857.73	90.4%	90.5%	92.4%	11.16	0.0039	0.09
44	93.4	2.4	2.1	0.5	1.6	8037.28	91.2%	90.8%	92.8%	10.37	0.0039	0.08
45	93.1	2.5	2.4	0.4	1.6	8217.78	90.1%	90.6%	92.3%	10.39	0.0039	0.08
46	93.2	2.5	2.2	0.4	1.6	8397.36	90.8%	90.6%	92.5%	9.62	0.0039	0.08
47	93.4	2.4	2.1	0.5	1.6	8576.66	91.0%	90.9%	92.6%	10.31	0.0039	0.08
48	93.3	2.4	2.2	0.4	1.6	8819.49	90.6%	90.8%	92.4%	10.30	0.0039	0.08
49	93.1	2.4	2.3	0.5	1.6	8999.30	90.2%	90.8%	92.3%	10.29	0.0039	0.08
50	93.4	2.4	2.2	0.4	1.6	9178.67	90.9%	90.9%	92.5%	9.63	0.0039	0.08
51	93.2	2.4	2.3	0.5	1.6	9358.75	90.5%	90.9%	92.5%	9.52	0.0039	0.08
52	93.3	2.4	2.3	0.4	1.6	9538.90	90.6%	90.8%	92.3%	9.53	0.0039	0.08
53	93.5	2.3	2.2	0.4	1.6	9718.31	90.9%	91.1%	92.7%	8.72	0.0039	0.07
54	93.1	2.4	2.3	0.5	1.7	9898.54	90.5%	90.7%	92.2%	10.27	0.0039	0.08

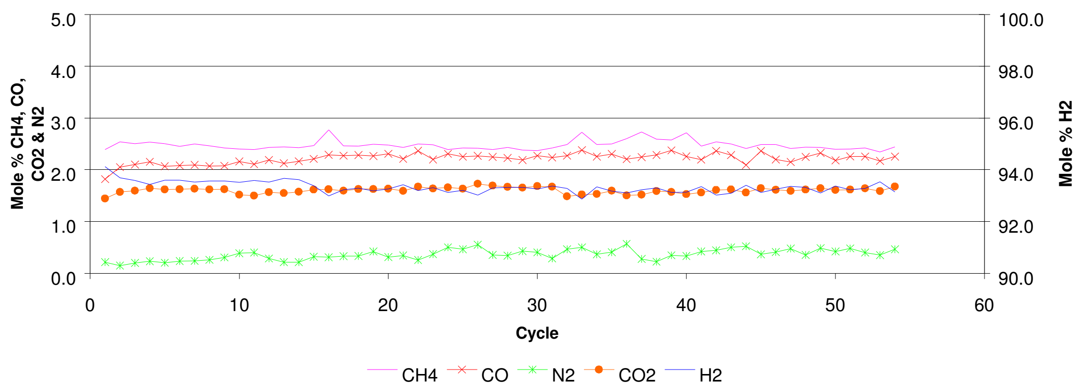
Average Reaction Efficiencies ECM 255019 & Engelhard Escat 326

Average Reaction Efficiencies
ECM 255019 & Engelhard Escat 326



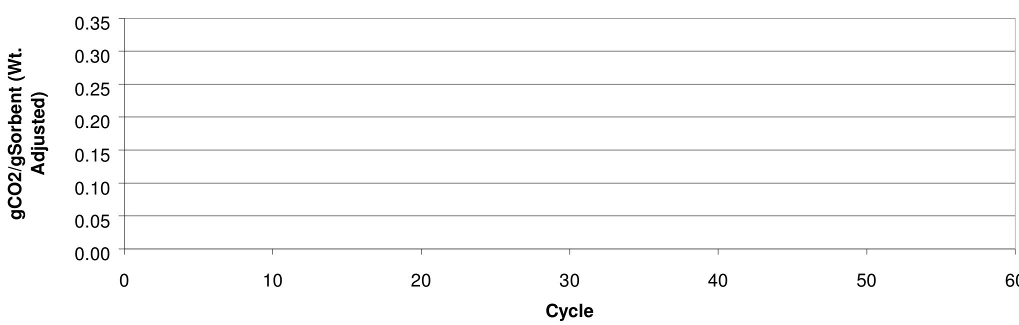
Average Reformate Composition ECM 255019 & Engelhard Escat 326

Average Reformate Composition
ECM 255019 & Engelhard Escat 326



gCO2 Sorbed per g Sorbent ECM 255019 & Engelhard Escat 326

gCO2 Sorbed per g Sorbent
ECM 255019 & Engelhard Escat 326

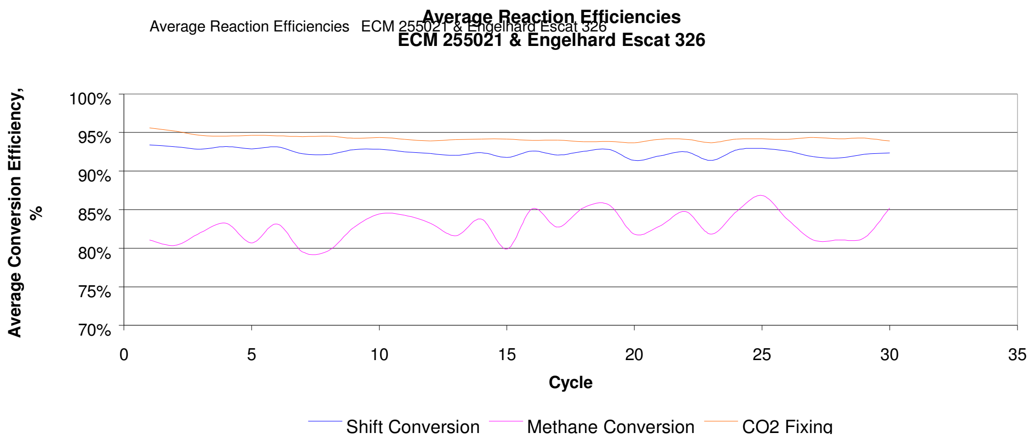


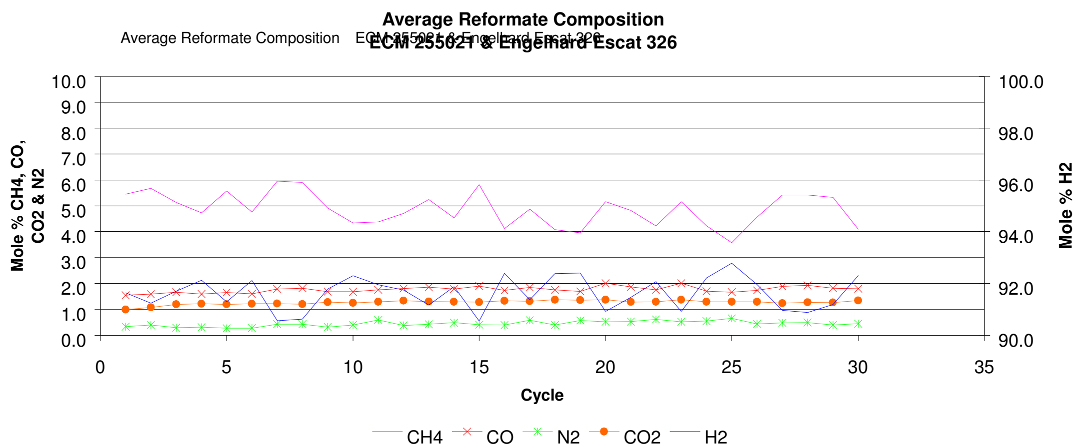
CO_2 Sorption Catalyst	ECM 255021
Reforming Catalyst: 0.5% rhodium o	Engelhard Escat 326
Composition CO_2 sorb	CaO/Al2O3 (90/10)
Binder	10%Al203
Batch No.	PCB954103A-1
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

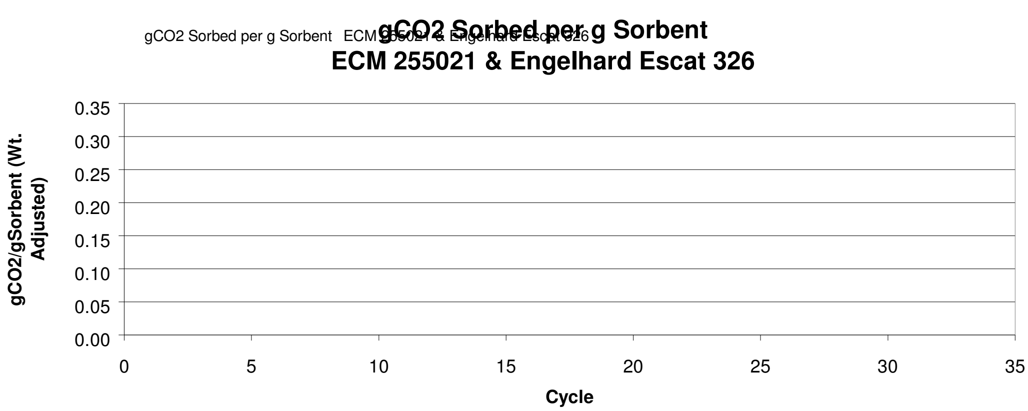
Wt. CO2 extrudate, g	19.63
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.6
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	24.13
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	91.6	5.5	1.5	0.3	1.0	211.05	93.4%	81.1%	95.6%	25.52	0.0047	0.31
2	91.2	5.7	1.6	0.4	1.1	387.40	93.2%	80.4%	95.2%	21.53	0.0046	0.26
3	91.7	5.1	1.7	0.3	1.2	567.38	92.9%	82.0%	94.6%	20.86	0.0047	0.24
4	92.1	4.7	1.6	0.3	1.2	744.12	93.2%	83.2%	94.5%	18.51	0.0048	0.22
5	91.3	5.6	1.7	0.3	1.2	920.53	92.9%	80.7%	94.6%	13.81	0.0046	0.16
6	92.1	4.8	1.6	0.3	1.2	1098.93	93.1%	83.2%	94.6%	12.80	0.0048	0.17
7	90.6	6.0	1.8	0.4	1.2	1277.80	92.2%	79.5%	94.5%	9.71	0.0045	0.12
8	90.6	5.9	1.8	0.4	1.2	1455.57	92.1%	79.7%	94.5%	7.66	0.0045	0.10
9	91.8	4.9	1.7	0.3	1.3	1639.56	92.8%	82.7%	94.2%	11.68	0.0047	0.14
10	92.3	4.3	1.7	0.4	1.3	1818.40	92.8%	84.4%	94.4%	12.60	0.0048	0.15
11	92.0	4.4	1.8	0.6	1.3	2015.30	92.5%	84.3%	94.1%	12.05	0.0048	0.16
12	91.7	4.7	1.8	0.4	1.3	2179.54	92.3%	83.2%	93.9%	13.28	0.0047	0.15
13	91.2	5.2	1.9	0.4	1.3	2356.88	92.0%	81.6%	94.1%	10.46	0.0046	0.14
14	91.9	4.5	1.8	0.5	1.3	2547.60	92.4%	83.8%	94.2%	10.42	0.0047	0.13
15	90.5	5.8	1.9	0.4	1.3	2715.71	91.8%	79.9%	94.1%	8.20	0.0045	0.12
16	92.4	4.1	1.7	0.4	1.3	2898.18	92.6%	85.1%	94.0%	11.01	0.0048	0.14
17	91.4	4.9	1.8	0.6	1.3	3076.03	92.1%	82.7%	94.0%	10.58	0.0047	0.11
18	92.4	4.1	1.8	0.4	1.4	3257.99	92.5%	85.2%	93.8%	10.95	0.0048	0.11
19	92.4	4.0	1.7	0.6	1.4	3437.02	92.8%	85.6%	93.9%	11.70	0.0049	0.12
20	90.9	5.2	2.0	0.5	1.4	4157.69	91.4%	81.8%	93.7%	10.46	0.0046	0.12
21	91.5	4.8	1.9	0.5	1.3	3797.10	92.0%	82.9%	94.1%	9.52	0.0047	0.11
22	92.1	4.2	1.8	0.6	1.3	3976.08	92.5%	84.8%	94.1%	10.29	0.0048	0.12
23	90.9	5.2	2.0	0.5	1.4	4157.69	91.4%	81.8%	93.7%	10.46	0.0046	0.12
24	92.2	4.2	1.7	0.5	1.3	4336.12	92.7%	84.8%	94.1%	10.25	0.0048	0.12
25	92.8	3.6	1.7	0.7	1.3	4516.17	92.9%	86.9%	94.2%	10.29	0.0049	0.13
26	92.0	4.6	1.7	0.4	1.3	4696.78	92.6%	83.7%	94.1%	10.46	0.0047	0.12
27	91.0	5.4	1.9	0.5	1.2	4875.18	91.9%	81.1%	94.4%	8.28	0.0046	0.10
28	90.9	5.4	1.9	0.5	1.3	5063.61	91.7%	81.1%	94.2%	9.20	0.0046	0.11
29	91.2	5.3	1.8	0.4	1.3	5235.88	92.2%	81.4%	94.3%	9.38	0.0046	0.10
30	92.3	4.1	1.8	0.4	1.3	5417.08	92.4%	85.2%	93.9%	10.09	0.0048	0.12


Average Reaction Efficiencies ECM 255021 & Engelhard Escat 326
Average Reaction Efficiencies
ECM 255021 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
0
5
10
15
20
25
30
35
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM 255021 & Engelhard Escat 326
Average Reformate Composition
ECM 255021 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
5
10
15
20
25
30
35
Cycle
CH4
CO
N2
CO2
H2

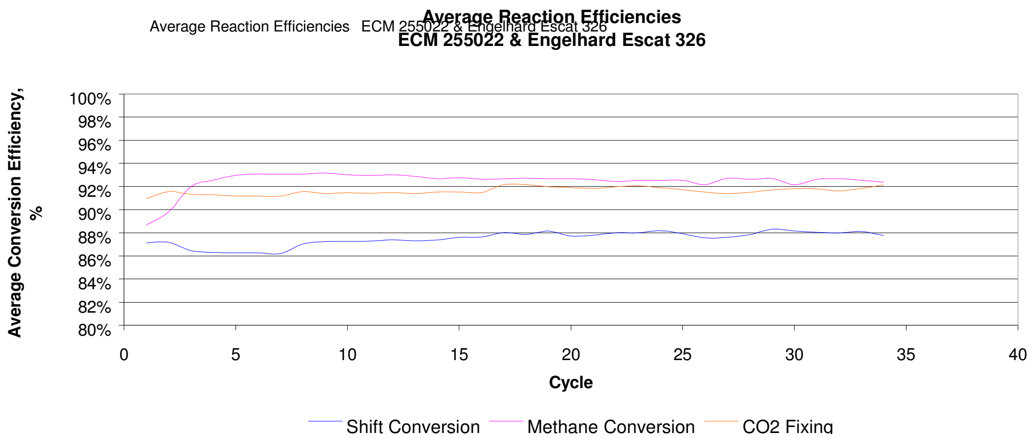

gCO2 Sorbed per g Sorbent ECM 255021 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM 255021 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
Cycle

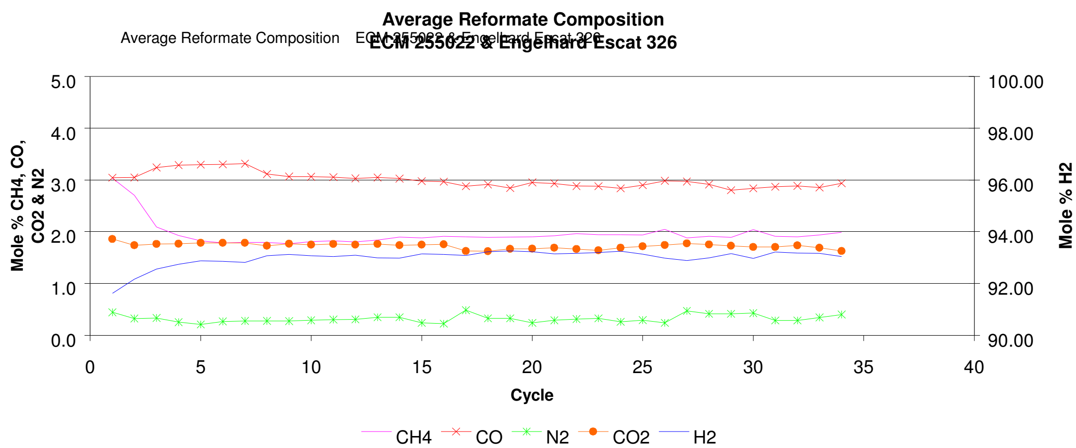
CO_2 Sorption Catalyst	ECM 255022
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/Al2O3 (90/10)
Binder	15%Al203
Batch No.	PCB954103A-1
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

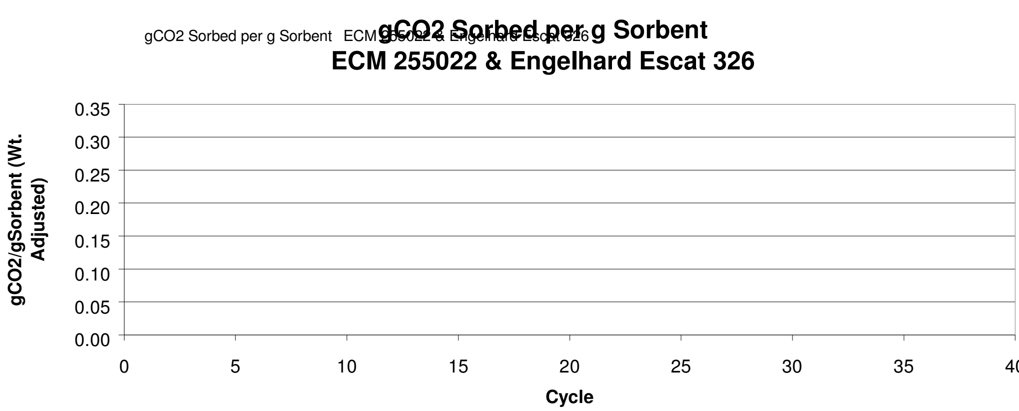
Wt. CO2 extrudate, g	19.99
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.6
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	24.49
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	91.61	3.03	3.04	0.44	1.86	214.07	0.87	0.89	0.91	24.10	0.0045	0.27
2	92.16	2.70	3.05	0.32	1.74	391.51	0.87	0.90	0.92	22.42	0.0046	0.26
3	92.55	2.09	3.24	0.33	1.76	571.23	0.86	0.92	0.91	22.24	0.0046	0.26
4	92.74	1.93	3.29	0.25	1.77	750.10	0.86	0.93	0.91	20.77	0.0047	0.24
5	92.87	1.82	3.30	0.21	1.79	929.83	0.86	0.93	0.91	20.06	0.0047	0.23
6	92.85	1.78	3.30	0.27	1.79	1108.74	0.86	0.93	0.91	20.09	0.0047	0.24
7	92.81	1.79	3.31	0.28	1.78	1288.43	0.86	0.93	0.91	19.31	0.0047	0.23
8	93.07	1.79	3.12	0.28	1.73	1467.49	0.87	0.93	0.92	17.86	0.0047	0.21
9	93.12	1.77	3.06	0.27	1.77	1647.24	0.87	0.93	0.91	18.65	0.0047	0.22
10	93.08	1.81	3.06	0.29	1.75	1827.12	0.87	0.93	0.91	17.89	0.0047	0.21
11	93.04	1.82	3.05	0.30	1.76	2006.32	0.87	0.93	0.91	17.91	0.0047	0.21
12	93.09	1.80	3.03	0.31	1.75	2186.15	0.87	0.93	0.91	17.08	0.0048	0.20
13	92.99	1.84	3.05	0.35	1.76	2365.98	0.87	0.93	0.91	17.90	0.0047	0.21
14	92.98	1.90	3.03	0.35	1.74	2545.70	0.87	0.93	0.92	17.14	0.0047	0.20
15	93.14	1.88	2.98	0.24	1.75	2725.43	0.88	0.93	0.92	16.31	0.0048	0.19
16	93.13	1.91	2.97	0.23	1.76	2905.88	0.88	0.93	0.91	16.34	0.0047	0.19
17	93.09	1.90	2.88	0.48	1.63	3084.91	0.88	0.93	0.92	16.42	0.0048	0.20
18	93.23	1.89	2.91	0.33	1.62	3265.16	0.88	0.93	0.92	16.34	0.0048	0.20
19	93.25	1.90	2.85	0.33	1.67	3444.81	0.88	0.93	0.92	15.62	0.0048	0.19
20	93.22	1.90	2.95	0.24	1.67	3625.13	0.88	0.93	0.92	15.63	0.0048	0.19
21	93.15	1.92	2.93	0.29	1.69	3805.43	0.88	0.93	0.92	15.58	0.0048	0.19
22	93.16	1.96	2.88	0.31	1.66	3984.27	0.88	0.92	0.92	15.54	0.0048	0.19
23	93.19	1.94	2.88	0.33	1.64	4164.63	0.88	0.93	0.92	15.66	0.0048	0.19
24	93.25	1.94	2.84	0.26	1.69	4344.09	0.88	0.93	0.92	14.86	0.0048	0.18
25	93.13	1.94	2.90	0.29	1.72	4524.33	0.88	0.93	0.92	14.91	0.0048	0.18
26	92.98	2.04	2.98	0.24	1.74	4708.26	0.88	0.92	0.92	14.11	0.0047	0.17
27	92.88	1.88	2.97	0.47	1.77	4883.38	0.88	0.93	0.91	14.97	0.0047	0.18
28	92.99	1.91	2.92	0.41	1.75	5064.22	0.88	0.93	0.91	15.03	0.0048	0.18
29	93.15	1.89	2.80	0.41	1.73	5243.47	0.88	0.93	0.92	14.91	0.0048	0.18
30	92.97	2.04	2.84	0.43	1.70	5423.34	0.88	0.92	0.92	14.12	0.0048	0.17
31	93.21	1.91	2.87	0.28	1.70	5603.66	0.88	0.93	0.92	14.11	0.0048	0.17
32	93.17	1.90	2.89	0.28	1.73	5783.99	0.88	0.93	0.92	14.08	0.0048	0.17
33	93.16	1.93	2.86	0.34	1.69	5963.08	0.88	0.93	0.92	14.21	0.0048	0.17
34	93.04	1.99	2.94	0.40	1.63	6143.30	0.88	0.92	0.92	14.18	0.0048	0.17


Average Reaction Efficiencies ECM 255022 & Engelhard Escat 326
Average Reaction Efficiencies
ECM 255022 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
5
10
15
20
25
30
35
40
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM 255022 & Engelhard Escat 326
Average Reformate Composition
ECM 255022 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.00
98.00
96.00
94.00
92.00
90.00
0
5
10
15
20
25
30
35
40
Cycle
CH4
CO
N2
CO2
H2

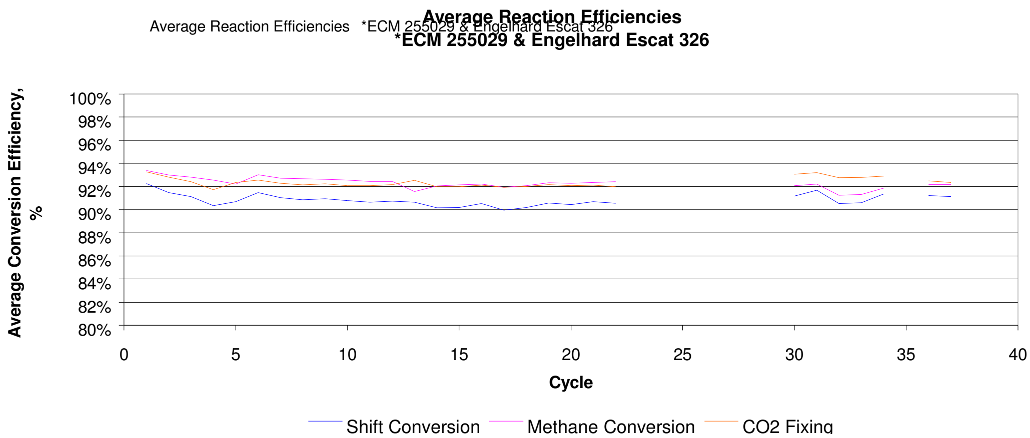

gCO2 Sorbed per g Sorbent ECM 255022 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM 255022 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
40
Cycle

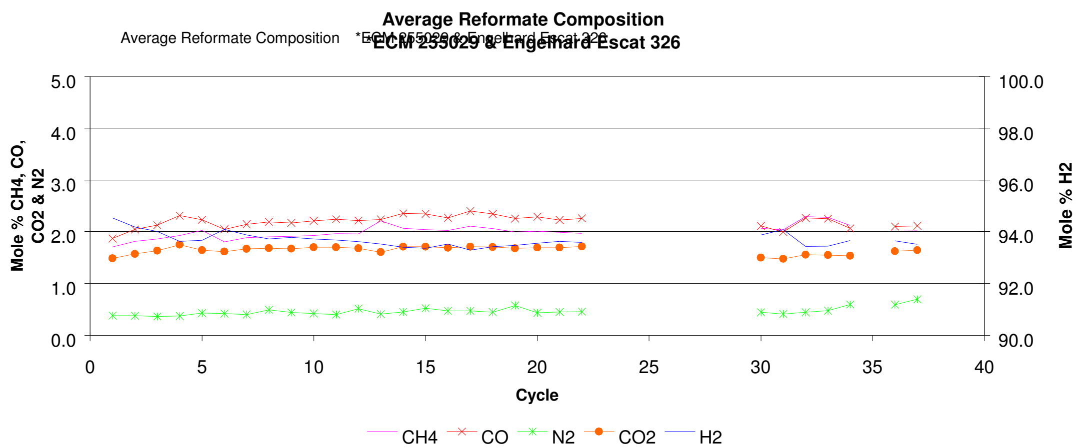
CO_2 Sorption Catalyst	*ECM 255029
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	*CaO/Al203 (95/5)
Binder	15%Al203
Batch No.	PCB952502A-2
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

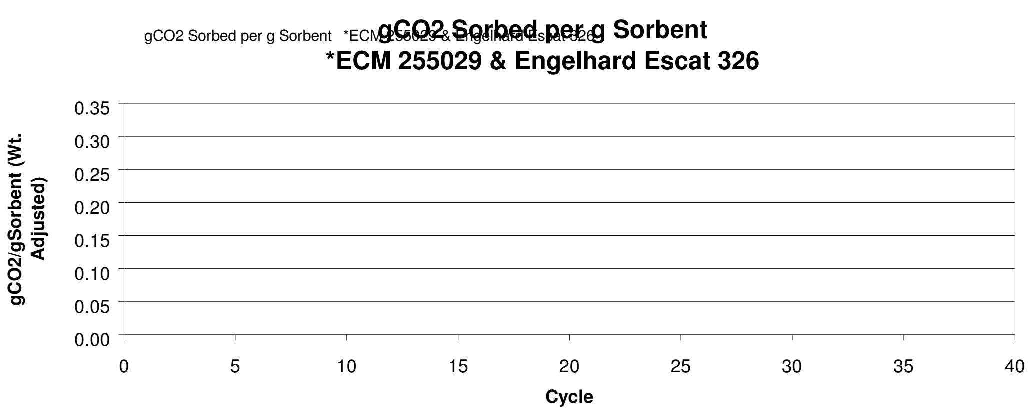
Wt. CO2 extrudate, g	24.98
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	29.48
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	94.5	1.7	1.9	0.4	1.5	510.86	92.3%	93.4%	93.3%	29.40	0.0041	0.29
2	94.2	1.8	2.0	0.4	1.6	691.34	91.5%	93.0%	92.8%	29.44	0.0040	0.29
3	94.0	1.9	2.1	0.4	1.6	870.20	91.1%	92.8%	92.4%	28.85	0.0040	0.28
4	93.6	1.9	2.3	0.4	1.7	1050.94	90.3%	92.6%	91.7%	29.45	0.0039	0.28
5	93.7	2.0	2.2	0.4	1.6	1227.53	90.7%	92.2%	92.3%	26.55	0.0040	0.26
6	94.1	1.8	2.0	0.4	1.6	1406.83	91.5%	93.0%	92.5%	24.82	0.0040	0.24
7	93.9	1.9	2.1	0.4	1.7	1586.01	91.0%	92.7%	92.3%	24.64	0.0040	0.24
8	93.7	1.9	2.2	0.5	1.7	1765.28	90.9%	92.7%	92.2%	24.78	0.0040	0.24
9	93.8	1.9	2.2	0.4	1.7	1944.53	90.9%	92.6%	92.2%	23.16	0.0040	0.22
10	93.7	1.9	2.2	0.4	1.7	2123.86	90.8%	92.6%	92.1%	23.07	0.0040	0.22
11	93.7	2.0	2.2	0.4	1.7	2303.54	90.6%	92.4%	92.1%	21.95	0.0039	0.21
12	93.6	2.0	2.2	0.5	1.7	2481.78	90.7%	92.4%	92.2%	21.60	0.0040	0.21
13	93.5	2.2	2.2	0.4	1.6	2663.40	90.6%	91.6%	92.5%	19.48	0.0039	0.19
14	93.4	2.1	2.4	0.4	1.7	2840.90	90.2%	92.1%	92.0%	20.39	0.0039	0.19
15	93.4	2.0	2.3	0.5	1.7	3020.40	90.2%	92.1%	92.0%	19.57	0.0039	0.19
16	93.5	2.0	2.3	0.5	1.7	3199.74	90.5%	92.2%	92.1%	18.85	0.0039	0.18
17	93.3	2.1	2.4	0.5	1.7	3380.00	90.0%	91.9%	91.9%	18.69	0.0039	0.18
18	93.4	2.1	2.3	0.4	1.7	3559.05	90.2%	92.1%	92.0%	18.17	0.0039	0.17
19	93.5	2.0	2.3	0.6	1.7	3738.06	90.6%	92.3%	92.2%	17.61	0.0039	0.17
20	93.6	2.0	2.3	0.4	1.7	3917.94	90.4%	92.3%	92.1%	17.06	0.0039	0.16
21	93.6	2.0	2.2	0.4	1.7	4097.82	90.7%	92.4%	92.1%	16.51	0.0039	0.16
22	93.6	2.0	2.3	0.5	1.7	4277.34	90.6%	92.4%	92.0%	16.61	0.0039	0.16
23												
24												
25												
26												
27												
28												
29												
30	93.9	2.1	2.1	0.4	1.5	5718.02	91.2%	92.1%	93.1%	17.46	0.0040	0.17
31	94.1	2.0	2.0	0.4	1.5	5897.39	91.7%	92.2%	93.2%	17.02	0.0040	0.17
32	93.4	2.3	2.3	0.4	1.6	6076.92	90.5%	91.3%	92.8%	16.07	0.0039	0.15
33	93.4	2.3	2.2	0.5	1.5	6255.96	90.6%	91.3%	92.8%	16.07	0.0039	0.15
34	93.7	2.1	2.1	0.6	1.5	6436.49	91.4%	91.9%	92.9%	16.22	0.0040	0.16
35												
36	93.6	2.0	2.1	0.6	1.6	9670.65	91.2%	92.2%	92.5%	10.81	0.0040	0.10
37	93.5	2.0	2.1	0.7	1.6	9850.74	91.1%	92.2%	92.4%	10.88	0.0040	0.11


Average Reaction Efficiencies *ECM 255029 & Engelhard Escat 326
Average Reaction Efficiencies
*ECM 255029 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
5
10
15
20
25
30
35
40
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *ECM 255029 & Engelhard Escat 326
Average Reformate Composition
*ECM 255029 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
5
10
15
20
25
30
35
40
Cycle
CH4
CO
N2
CO2
H2

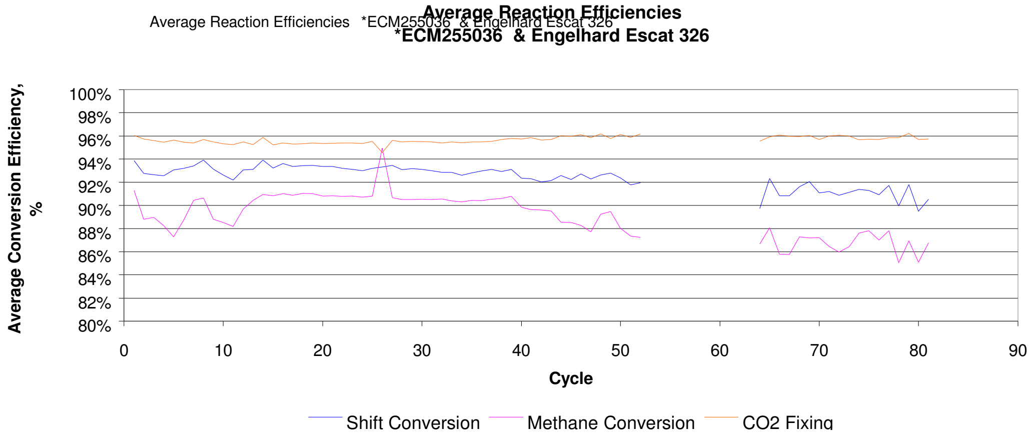

gCO2 Sorbed per g Sorbent *ECM 255029 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*ECM 255029 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
40
Cycle

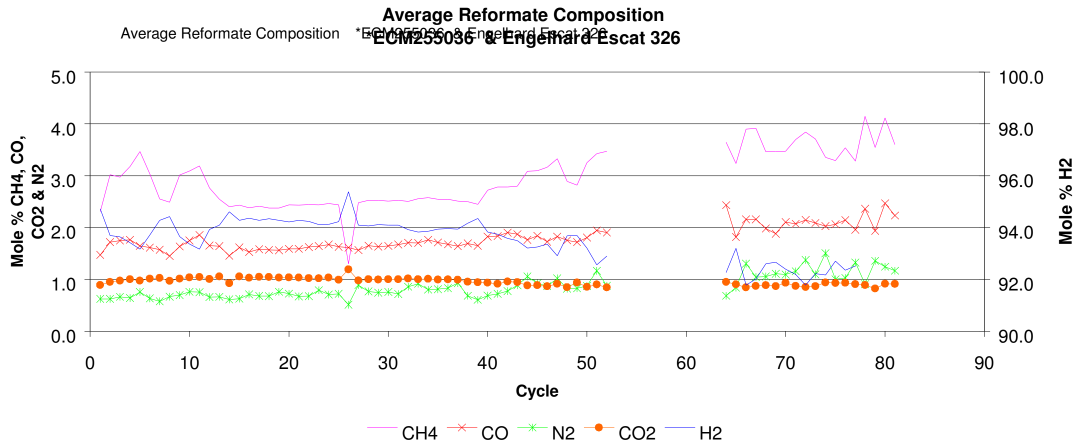
CO_2 Sorption Catalyst	*ECM255036
Reforming Catalyst: 0.5% rhodium o	Engelhard Escat 326
Composition CO_2 sorb	*CaO/Al203 (90/10)
Binder	15%Al203
Batch No.	ECM255032 + ECM255033
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

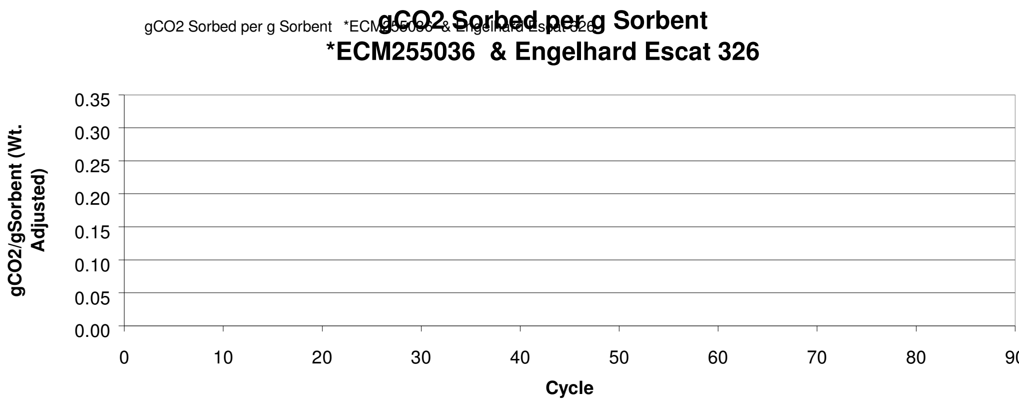
Wt. CO2 extrudate, g	27
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	31.5
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	94.7	2.3	1.5	0.6	0.9	209.62	93.9%	91.3%	96.0%	30.26	0.0039	0.31
2	93.7	3.0	1.7	0.6	0.9	390.27	92.8%	88.8%	95.7%	29.57	0.0037	0.29
3	93.6	3.0	1.7	0.7	1.0	568.96	92.6%	89.0%	95.6%	29.41	0.0037	0.29
4	93.4	3.2	1.8	0.6	1.0	747.38	92.6%	88.2%	95.5%	26.57	0.0037	0.26
5	93.2	3.5	1.6	0.8	1.0	924.20	93.1%	87.3%	95.6%	24.47	0.0037	0.24
6	93.7	3.0	1.6	0.6	1.0	1104.68	93.2%	88.7%	95.5%	24.05	0.0037	0.24
7	94.3	2.5	1.6	0.6	1.0	1284.00	93.4%	90.4%	95.4%	23.82	0.0038	0.24
8	94.4	2.5	1.5	0.7	1.0	1461.75	93.9%	90.6%	95.7%	21.77	0.0039	0.22
9	93.6	3.0	1.6	0.7	1.0	1641.84	93.1%	88.8%	95.5%	21.74	0.0037	0.22
10	93.4	3.1	1.7	0.8	1.0	1821.74	92.6%	88.5%	95.3%	21.69	0.0037	0.21
11	93.2	3.2	1.9	0.8	1.0	2001.27	92.2%	88.2%	95.3%	21.36	0.0037	0.21
12	93.9	2.8	1.7	0.7	1.0	2180.77	93.1%	89.7%	95.5%	20.19	0.0038	0.20
13	94.1	2.5	1.6	0.7	1.1	2360.87	93.1%	90.4%	95.3%	21.21	0.0038	0.21
14	94.6	2.4	1.5	0.6	0.9	2540.22	93.9%	91.0%	95.9%	19.58	0.0039	0.20
15	94.3	2.4	1.6	0.6	1.1	2720.57	93.2%	90.8%	95.2%	20.70	0.0038	0.21
16	94.4	2.4	1.5	0.7	1.0	2899.40	93.6%	91.0%	95.4%	19.68	0.0038	0.20
17	94.3	2.4	1.6	0.7	1.0	3079.20	93.4%	90.9%	95.3%	19.69	0.0038	0.20
18	94.3	2.4	1.6	0.7	1.0	3258.65	93.4%	91.0%	95.3%	18.66	0.0038	0.19
19	94.3	2.4	1.6	0.8	1.0	3438.09	93.5%	91.0%	95.4%	18.12	0.0038	0.19
20	94.2	2.4	1.6	0.7	1.0	3617.46	93.4%	90.8%	95.3%	17.55	0.0038	0.18
21	94.3	2.4	1.6	0.7	1.0	3797.18	93.4%	90.8%	95.4%	16.42	0.0038	0.17
22	94.2	2.4	1.6	0.7	1.0	3976.59	93.2%	90.8%	95.4%	16.41	0.0038	0.17
23	94.1	2.4	1.6	0.8	1.0	4155.96	93.1%	90.8%	95.4%	15.90	0.0038	0.16
24	94.1	2.5	1.7	0.7	1.0	4335.40	93.0%	90.7%	95.3%	15.36	0.0038	0.16
25	94.2	2.4	1.6	0.7	1.0	4514.57	93.2%	90.8%	95.5%	14.23	0.0038	0.15
26	95.4	1.3	1.6	0.5	1.2	4694.21	93.3%	94.9%	94.6%	14.36	0.0040	0.15
27	94.1	2.5	1.6	0.9	1.0	4873.15	93.5%	90.7%	95.6%	13.83	0.0038	0.14
28	94.1	2.5	1.6	0.8	1.0	5053.73	93.1%	90.5%	95.5%	13.34	0.0038	0.14
29	94.1	2.5	1.6	0.7	1.0	5232.76	93.2%	90.5%	95.5%	12.70	0.0038	0.13
30	94.1	2.5	1.6	0.8	1.0	5412.79	93.1%	90.5%	95.5%	12.23	0.0038	0.12
31	94.1	2.5	1.7	0.7	1.0	5592.47	93.0%	90.5%	95.5%	12.22	0.0038	0.12
32	93.9	2.5	1.7	0.9	1.0	5772.13	92.9%	90.6%	95.4%	12.16	0.0038	0.12
33	93.8	2.6	1.7	0.9	1.0	5951.60	92.9%	90.4%	95.5%	12.17	0.0038	0.12
34	93.8	2.6	1.8	0.8	1.0	6131.98	92.6%	90.3%	95.4%	11.65	0.0038	0.12
35	93.9	2.5	1.7	0.8	1.0	6311.36	92.8%	90.4%	95.5%	11.59	0.0038	0.12
36	94.0	2.5	1.7	0.8	1.0	6491.23	93.0%	90.4%	95.5%	11.12	0.0038	0.11
37	93.9	2.5	1.6	0.9	1.0	6670.92	93.1%	90.5%	95.5%	10.61	0.0038	0.11
38	94.2	2.5	1.7	0.7	1.0	464.62	92.9%	90.6%	95.7%	11.76	0.0038	0.12
39	94.3	2.4	1.6	0.6	0.9	643.86	93.1%	90.8%	95.8%	10.79	0.0038	0.11
40	93.8	2.7	1.8	0.7	0.9	823.85	92.3%	89.8%	95.7%	10.32	0.0038	0.10
41	93.7	2.8	1.8	0.7	0.9	1003.99	92.3%	89.6%	95.8%	11.05	0.0038	0.11
42	93.6	2.8	1.9	0.8	1.0	1183.87	92.0%	89.6%	95.6%	10.62	0.0037	0.11
43	93.5	2.8	1.9	0.9	0.9	1363.57	92.1%	89.5%	95.7%	10.16	0.0037	0.10
44	93.2	3.1	1.8	1.1	0.9	1542.50	92.6%	88.5%	96.0%	10.09	0.0037	0.10
45	93.2	3.1	1.8	0.9	0.9	1723.05	92.2%	88.5%	96.0%	9.59	0.0037	0.09
46	93.4	3.2	1.7	0.9	0.9	1902.34	92.7%	88.3%	96.1%	8.95	0.0037	0.09
47	92.9	3.3	1.8	1.0	0.9	2082.34	92.3%	87.7%	95.8%	8.97	0.0037	0.09
48	93.7	2.9	1.8	0.8	0.8	2262.01	92.6%	89.2%	96.2%	9.02	0.0038	0.09
49	93.7	2.8	1.7	0.8	0.9	2441.98	92.8%	89.5%	95.8%	8.55	0.0038	0.09
50	93.2	3.2	1.8	0.9	0.9	2621.09	92.4%	88.0%	96.1%	8.03	0.0037	0.08
51	92.6	3.4	1.9	1.2	0.9	2801.22	91.8%	87.4%	95.9%	8.44	0.0036	0.08
52	92.9	3.5	1.9	0.9	0.8	2981.31	92.0%	87.2%	96.2%	7.98	0.0036	0.08
53												
54												
55												
56												
57												
58												
59												
60												
61												
62												
63												
64	92.3	3.6	2.4	0.7	0.9	6225.63	89.7%	86.7%	95.6%	3.65	0.0035	0.03
65	93.2	3.2	1.8	0.8	0.9	6401.27	92.3%	88.1%	95.9%	7.17	0.0037	0.07
66	91.8	3.9	2.2	1.3	0.8	6581.40	90.8%	85.8%	96.1%	7.54	0.0035	0.07
67	92.0	3.9	2.2	1.0	0.9	6761.57	90.8%	85.8%	96.0%	7.95	0.0035	0.07
68	92.6	3.5	2.0	1.1	0.9	6941.54	91.6%	87.3%	95.9%	7.93	0.0036	0.08
69	92.7	3.5	1.9	1.1	0.9	7120.75	92.1%	87.2%	96.0%	6.41	0.0036	0.06
70	92.4	3.5	2.1	1.1	0.9	7301.44	91.1%	87.2%	95.7%	7.90	0.0036	0.08
71	92.2	3.7	2.1	1.2	0.9	7480.64	91.2%	86.5%	96.0%	6.44	0.0036	0.06
72	91.8	3.8	2.1	1.4	0.8	7660.50	90.9%	86.0%	96.1%	7.08	0.0036	0.07
73	92.2	3.7	2.1	1.1	0.9	7840.75	91.1%	86.4%	96.0%	6.48	0.0036	0.06
74	92.2	3.4	2.0	1.5	0.9	8020.76	91.4%	87.6%	95.7%	8.00	0.0036	0.08
75	92.7	3.3	2.1	1.0	0.9	8200.78	91.3%	87.8%	95.7%	6.55	0.0036	0.06
76	92.4	3.5	2.1	1.0	0.9	8380.73	90.9%	87.0%	95.7%	7.11	0.0036	0.07
77	92.5	3.3	2.0	1.3	0.9	8559.78	91.7%	87.8%	95.8%	6.44	0.0037	0.06
78	91.7	4.1	2.4	0.9	0.9	8741.30	90.0%	85.1%	95.8%	7.06	0.0035	0.07
79	92.3	3.5	1.9	1.4	0.8	8919.18	91.8%	86.9%	96.2%	5.72	0.0036	0.06
80	91.2	4.1	2.5	1.2	0.9	9101.29	89.5%	85.1%	95.7%	7.02	0.0034	0.06
81	92.1	3.6	2.2	1.2	0.9	9280.05	90.5%	86.8%	95.7%	6.45	0.0036	0.06


Average Reaction Efficiencies *ECM255036 & Engelhard Escat 326
Average Reaction Efficiencies
*ECM255036 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
70
80
90
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *ECM255036 & Engelhard Escat 326
Average Reformate Composition
*ECM255036 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
10
20
30
40
50
60
70
80
90
Cycle
CH4
CO
N2
CO2
H2

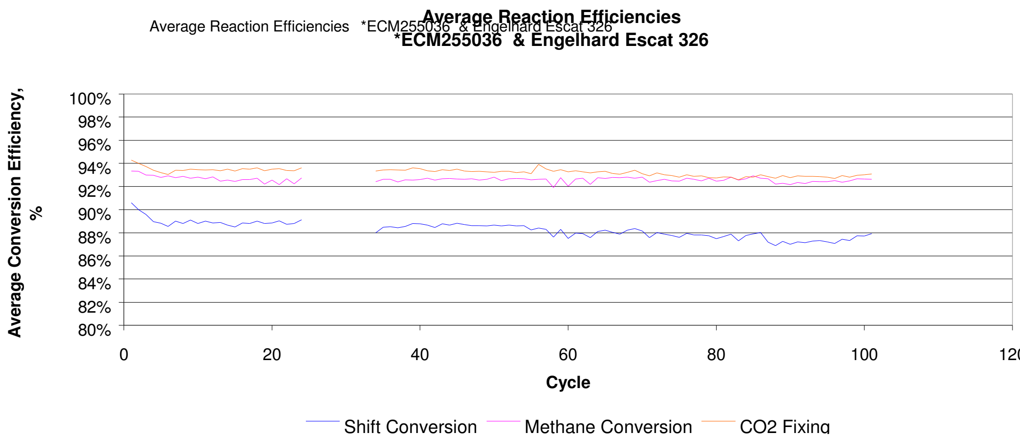

gCO2 Sorbed per g Sorbent *ECM255036 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*ECM255036 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
90
Cycle

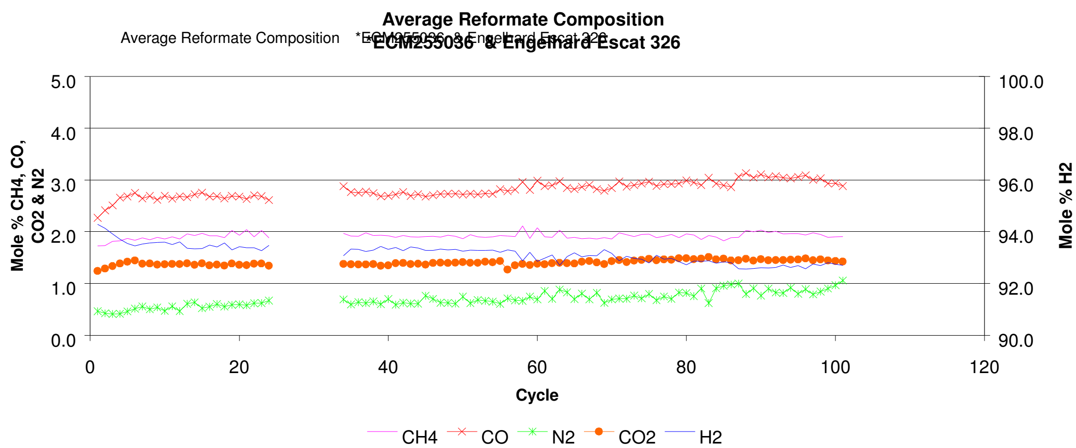
CO_2 Sorption Catalyst	*ECM255036
Reforming Catalyst: 0.5% rhodium on	Engelhard Escat 326
Composition CO_2 sorb	*CaO/Al203 (90/10)
Binder	15%Al203
Batch No.	ECM255032 + ECM255033
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

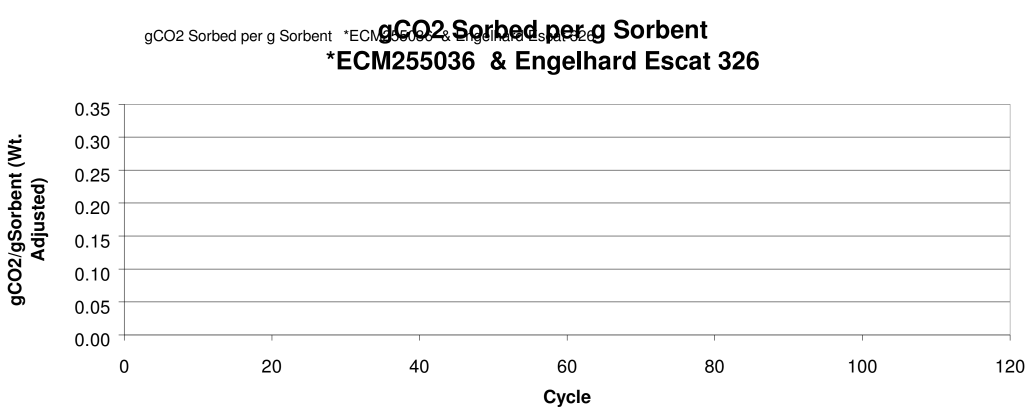
Wt. CO2 extrudate, g	30
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.9
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	34.5
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	94.3	1.7	2.3	0.5	1.2	7343.51	90.6%	93.3%	94.3%	29.53	0.1002	0.22
2	94.1	1.7	2.4	0.4	1.3	7523.55	90.0%	93.3%	94.0%	29.48	0.0991	0.22
3	93.9	1.8	2.5	0.4	1.3	7703.70	89.6%	93.0%	93.7%	29.57	0.0983	0.22
4	93.7	1.8	2.7	0.4	1.4	7884.08	89.0%	93.0%	93.4%	29.51	0.0971	0.21
5	93.5	1.9	2.7	0.5	1.4	8064.07	88.8%	92.8%	93.2%	29.42	0.0963	0.21
6	93.4	1.8	2.7	0.5	1.4	8243.50	88.6%	92.9%	93.0%	30.09	0.0981	0.22
7	93.5	1.9	2.6	0.6	1.4	8421.56	89.0%	92.8%	93.4%	27.76	0.0912	0.20
8	93.6	1.8	2.7	0.5	1.4	8600.92	88.8%	92.9%	93.4%	27.25	0.0894	0.20
9	93.6	1.9	2.6	0.5	1.4	8780.13	89.1%	92.7%	93.5%	26.10	0.0859	0.19
10	93.6	1.9	2.7	0.5	1.4	8959.98	88.8%	92.8%	93.5%	25.75	0.0845	0.19
11	93.5	1.9	2.6	0.6	1.4	9139.35	89.0%	92.7%	93.4%	25.59	0.0840	0.18
12	93.6	1.9	2.7	0.5	1.4	9319.19	88.9%	92.8%	93.4%	24.97	0.0820	0.18
13	93.4	2.0	2.7	0.6	1.4	9498.63	88.9%	92.5%	93.4%	25.11	0.0821	0.18
14	93.3	1.9	2.7	0.6	1.4	9678.24	88.7%	92.6%	93.5%	24.39	0.0797	0.17
15	93.4	2.0	2.8	0.5	1.4	9858.06	88.5%	92.4%	93.3%	23.72	0.0772	0.17
16	93.5	1.9	2.7	0.5	1.3	10037.41	88.9%	92.6%	93.6%	22.82	0.0748	0.16
17	93.4	1.9	2.7	0.6	1.4	10216.29	88.8%	92.6%	93.5%	22.65	0.0742	0.16
18	93.6	1.9	2.6	0.6	1.3	10396.13	89.0%	92.7%	93.6%	21.88	0.0720	0.16
19	93.3	2.0	2.7	0.6	1.4	10576.12	88.8%	92.2%	93.4%	22.36	0.0728	0.16
20	93.4	1.9	2.7	0.6	1.4	10755.24	88.8%	92.6%	93.5%	21.22	0.0695	0.15
21	93.4	2.0	2.6	0.6	1.4	10934.80	89.0%	92.2%	93.5%	20.71	0.0677	0.15
22	93.4	1.9	2.7	0.6	1.4	11114.35	88.7%	92.7%	93.4%	20.49	0.0670	0.15
23	93.3	2.0	2.7	0.6	1.4	11294.76	88.8%	92.2%	93.4%	20.17	0.0657	0.14
24	93.5	1.9	2.6	0.7	1.3	11472.99	89.1%	92.7%	93.6%	19.49	0.0642	0.14
25												
26												
27												
28	Water rate 1/2 <90% H2 for 8 cycles											
29												
30												
31												
32												
33												
34	93.1	2.0	2.9	0.7	1.4	13089.49	88.0%	92.4%	93.3%	15.08	0.0488	0.11
35	93.3	1.9	2.8	0.6	1.4	13270.61	88.5%	92.6%	93.4%	16.22	0.0529	0.12
36	93.3	1.9	2.8	0.6	1.4	13451.07	88.5%	92.6%	93.4%	16.80	0.0549	0.12
37	93.2	2.0	2.8	0.6	1.4	13630.88	88.4%	92.4%	93.4%	16.83	0.0547	0.12
38	93.3	1.9	2.7	0.7	1.4	13810.81	88.6%	92.6%	93.4%	16.64	0.0543	0.12
39	93.4	1.9	2.7	0.6	1.3	13990.29	88.8%	92.6%	93.6%	16.28	0.0534	0.12
40	93.3	1.9	2.7	0.7	1.3	14170.02	88.8%	92.6%	93.6%	16.16	0.0530	0.12
41	93.4	1.9	2.7	0.6	1.4	14350.62	88.7%	92.7%	93.4%	15.59	0.0510	0.11
42	93.3	1.9	2.8	0.6	1.4	14530.22	88.5%	92.6%	93.3%	16.13	0.0525	0.12
43	93.4	1.9	2.7	0.6	1.4	14709.89	88.8%	92.7%	93.5%	15.21	0.0498	0.11
44	93.4	1.9	2.7	0.6	1.4	14889.43	88.6%	92.7%	93.4%	15.56	0.0509	0.11
45	93.3	1.9	2.7	0.8	1.4	15068.90	88.8%	92.6%	93.5%	15.02	0.0492	0.11
46	93.3	1.9	2.7	0.7	1.4	15248.72	88.7%	92.6%	93.3%	15.18	0.0496	0.11
47	93.3	1.9	2.7	0.6	1.4	15429.08	88.6%	92.7%	93.3%	14.60	0.0476	0.10
48	93.3	1.9	2.7	0.6	1.4	15608.82	88.6%	92.6%	93.3%	14.12	0.0460	0.10
49	93.3	1.9	2.7	0.6	1.4	15788.62	88.6%	92.6%	93.3%	14.18	0.0462	0.10
50	93.2	1.9	2.7	0.7	1.4	15968.24	88.7%	92.8%	93.2%	14.08	0.0460	0.10
51	93.3	1.9	2.7	0.6	1.4	16147.80	88.6%	92.5%	93.3%	13.46	0.0438	0.10
52	93.3	1.9	2.7	0.7	1.4	16327.85	88.7%	92.7%	93.3%	13.47	0.0440	0.10
53	93.3	1.9	2.7	0.7	1.4	16507.46	88.6%	92.7%	93.2%	13.51	0.0440	0.10
54	93.3	1.9	2.7	0.6	1.4	16687.50	88.6%	92.7%	93.3%	12.91	0.0421	0.09
55	93.2	1.9	2.8	0.6	1.4	16867.45	88.2%	92.6%	93.1%	13.00	0.0421	0.09
56	93.3	1.9	2.8	0.7	1.3	17047.08	88.4%	92.6%	93.9%	13.02	0.0426	0.09
57	93.2	1.9	2.8	0.7	1.3	17227.33	88.3%	92.6%	93.5%	12.49	0.0407	0.09
58	92.9	2.1	3.0	0.7	1.4	17407.11	87.6%	91.9%	93.3%	12.34	0.0395	0.09
59	93.2	1.9	2.8	0.7	1.4	17586.82	88.3%	92.8%	93.5%	12.35	0.0403	0.09
60	92.9	2.1	3.0	0.7	1.4	17766.69	87.5%	92.0%	93.3%	12.47	0.0399	0.09
61	93.0	1.9	2.9	0.9	1.4	17946.37	88.0%	92.7%	93.4%	12.40	0.0402	0.09
62	93.1	1.9	2.9	0.7	1.4	18126.46	87.9%	92.7%	93.3%	12.39	0.0401	0.09
63	92.7	2.0	3.0	0.9	1.4	18306.31	87.6%	92.2%	93.2%	12.42	0.0398	0.09
64	93.0	1.9	2.8	0.8	1.4	18486.34	88.1%	92.8%	93.3%	11.91	0.0387	0.08
65	93.2	1.9	2.8	0.7	1.4	18665.84	88.2%	92.7%	93.3%	11.44	0.0372	0.08
66	93.0	1.9	2.9	0.8	1.4	18845.73	88.0%	92.8%	93.1%	11.38	0.0369	0.08
67	93.1	1.9	2.9	0.7	1.4	19025.68	87.9%	92.8%	93.1%	11.33	0.0366	0.08
68	93.1	1.9	2.8	0.8	1.4	19205.13	88.2%	92.8%	93.2%	10.85	0.0353	0.08
69	93.3	1.9	2.8	0.6	1.4	19385.23	88.4%	92.7%	93.4%	10.28	0.0335	0.07
70	93.2	1.9	2.8	0.7	1.4	19565.04	88.2%	92.8%	93.1%	10.31	0.0335	0.07
71	92.9	2.0	3.0	0.7	1.4	19745.11	87.6%	92.4%	92.9%	10.84	0.0347	0.08
72	93.0	1.9	2.9	0.7	1.4	19924.70	88.0%	92.5%	93.2%	9.71	0.0314	0.07
73	93.0	1.9	2.9	0.8	1.4	20104.85	87.9%	92.6%	93.0%	9.78	0.0316	0.07
74	92.9	1.9	2.9	0.7	1.5	20284.46	87.8%	92.5%	93.0%	9.71	0.0312	0.07
75	92.8	2.0	3.0	0.8	1.5	20464.49	87.6%	92.5%	92.8%	9.79	0.0314	0.07
76	93.1	1.9	2.9	0.7	1.4	20644.00	88.0%	92.7%	93.0%	9.28	0.0300	0.07
77	92.9	1.9	2.9	0.7	1.5	20824.05	87.8%	92.6%	92.9%	9.27	0.0298	0.07
78	93.0	1.9	2.9	0.7	1.5	21003.76	87.8%	92.5%	92.9%	9.28	0.0299	0.07
79	92.8	1.9	2.9	0.8	1.5	21183.79	87.7%	92.7%	92.8%	9.31	0.0299	0.07
80	92.7	2.0	3.0	0.8	1.5	21364.04	87.5%	92.5%	92.7%	8.95	0.0286	0.06
81	92.9	1.9	3.0	0.8	1.5	21543.65	87.7%	92.5%	92.8%	9.17	0.0294	0.06
82	92.9	1.9	2.9	0.9	1.5	21724.51	87.9%	92.8%	92.8%	8.73	0.0282	0.06
83	92.9	1.9	3.0	0.6	1.5	21905.07	87.3%	92.6%	92.6%	8.66	0.0276	0.06
84	92.8	1.9	2.9	0.9	1.5	22084.19	87.8%	92.7%	92.9%	8.65	0.0278	0.06
85	92.8	1.8	2.9	1.0	1.5	22263.75	87.9%	92.9%	92.8%	8.69	0.0281	0.06
86	92.8	1.9	2.9	1.0	1.4	22443.48	88.0%	92.7%	93.0%	7.97	0.0258	0.06
87	92.6	1.9	3.1	1.0	1.4	22624.55	87.2%	92.7%	92.9%	8.67	0.0277	0.06
88	92.6	2.0	3.1	0.8	1.5	22804.09	86.9%	92.2%	92.7%	8.01	0.0254	0.06
89	92.6	2.0	3.0	0.9	1.4	22984.05	87.3%	92.3%	92.9%	7.75	0.0247	0.05
90	92.6	2.0	3.1	0.8	1.5	23164.07	87.0%	92.2%	92.8%	7.77	0.0246	0.05
91	92.6	2.0	3.1	0.9	1.4	23343.79	87.2%	92.3%	92.9%	7.80	0.0249	0.05
92	92.6	2.0	3.1	0.8	1.5	23523.57	87.1%	92.3%	92.9%	7.71	0.0245	0.05
93	92.7	2.0	3.0	0.8	1.5	23703.63	87.3%	92.4%	92.9%	7.18	0.0229	0.05
94	92.6	2.0	3.0	0.9	1.5	23883.09	87.3%	92.4%	92.9%	7.67	0.0245	0.05
95	92.7	2.0	3.1	0.8	1.5	24063.51	87.2%	92.4%	92.8%	7.15	0.0228	0.05
96	92.6	1.9	3.1	0.9	1.5	24243.65	87.1%	92.5%	92.7%	7.14	0.0227	0.05
97	92.8	2.0	3.0	0.8	1.4	24423.00	87.5%	92.4%	92.9%	6.60	0.0211	0.05
98	92.7	1.9	3.0	0.8	1.5	24603.24	87.3%	92.5%	92.8%	6.71	0.0214	0.05
99	92.8	1.9	2.9	0.9	1.4	24782.42	87.8%	92.7%	93.0%	6.70	0.0216	0.05
100	92.7	1.9	2.9	1.0	1.4	24962.67	87.7%	92.7%	93.0%	6.72	0.0217	0.05
101	92.7	1.9	2.9	1.1	1.4	25141.97	87.9%	92.6%	93.1%	6.63	0.0214	0.05


Average Reaction Efficiencies *ECM255036 & Engelhard Escat 326
Average Reaction Efficiencies
*ECM255036 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
20
40
60
80
100
120
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *ECM255036 & Engelhard Escat 326
Average Reformate Composition
*ECM255036 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
20
40
60
80
100
120
Cycle
CH4
CO
N2
CO2
H2

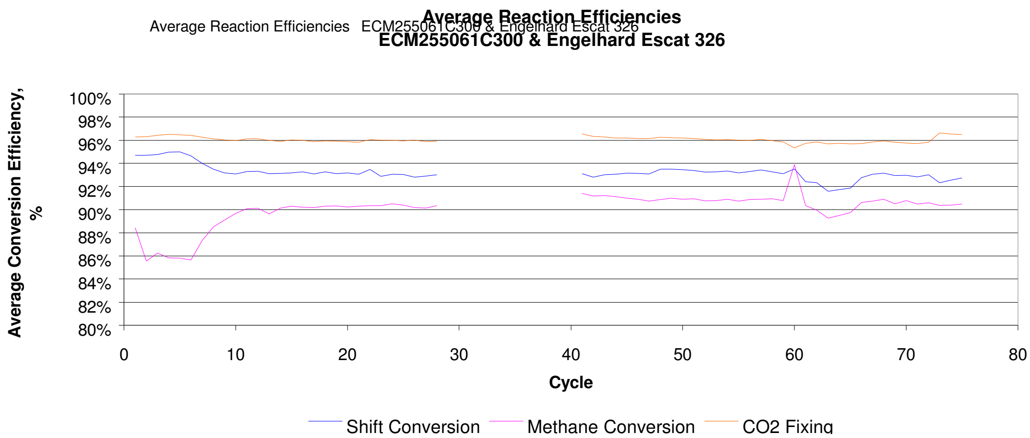

gCO2 Sorbed per g Sorbent *ECM255036 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*ECM255036 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
120
Cycle

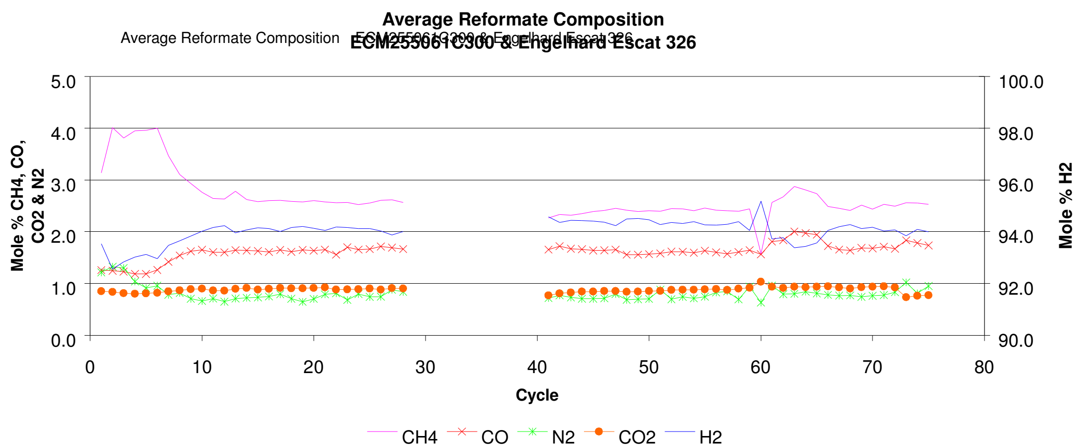
CO_2 Sorption Catalyst	ECM255061C300
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	*CaO/Al203 (90/10)
Binder	15%Al203
Batch No.	PCB954103A-1
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	300

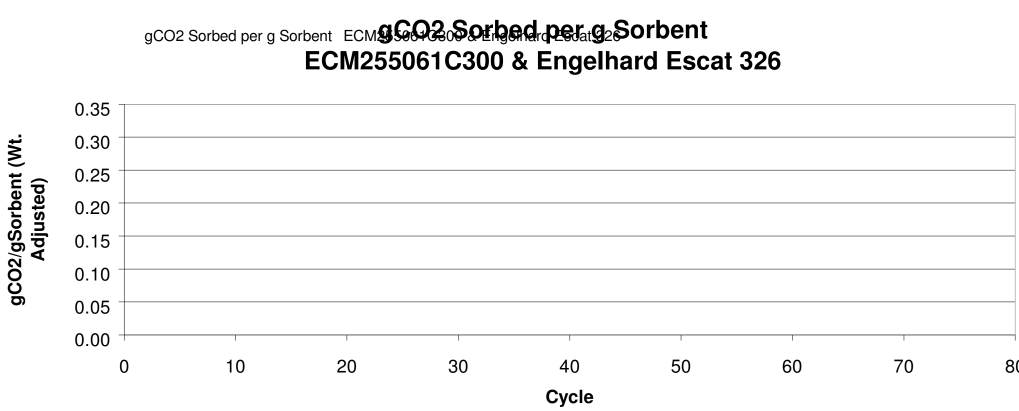
Wt. CO2 extrudate, g	32.16
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	1.0
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	36.66
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	93.5	3.1	1.3	1.2	0.9	88.01	94.7%	88.4%	96.3%	5.98	0.0383	0.06
2	92.6	4.0	1.2	1.3	0.8	267.38	94.7%	85.6%	96.3%	4.28	0.0265	0.04
3	92.8	3.8	1.2	1.3	0.8	449.37	94.8%	86.2%	96.4%	7.63	0.0477	0.07
4	93.0	4.0	1.2	1.0	0.8	634.01	95.0%	85.8%	96.5%	11.36	0.0710	0.11
5	93.1	4.0	1.2	0.9	0.8	818.98	95.0%	85.8%	96.5%	16.82	0.1050	0.16
6	93.0	4.0	1.3	1.0	0.8	1003.22	94.6%	85.7%	96.4%	21.14	0.1312	0.19
7	93.5	3.5	1.4	0.8	0.8	1187.59	94.0%	87.3%	96.3%	25.55	0.1604	0.24
8	93.6	3.1	1.5	0.8	0.9	1368.00	93.5%	88.5%	96.1%	25.96	0.1642	0.24
9	93.8	2.9	1.6	0.7	0.9	1548.03	93.2%	89.1%	96.0%	25.93	0.1643	0.24
10	94.0	2.8	1.6	0.7	0.9	1727.85	93.1%	89.7%	96.0%	25.24	0.1607	0.24
11	94.2	2.6	1.6	0.7	0.9	1906.73	93.3%	90.1%	96.1%	24.99	0.1604	0.24
12	94.2	2.6	1.6	0.6	0.9	2086.71	93.3%	90.1%	96.1%	23.69	0.1522	0.23
13	94.0	2.8	1.6	0.7	0.9	2266.53	93.1%	89.6%	96.0%	23.41	0.1491	0.22
14	94.1	2.6	1.6	0.7	0.9	2445.57	93.1%	90.1%	95.9%	23.17	0.1483	0.22
15	94.2	2.6	1.6	0.7	0.9	2625.95	93.2%	90.3%	96.0%	23.21	0.1491	0.22
16	94.1	2.6	1.6	0.7	0.9	2805.25	93.3%	90.2%	96.0%	23.19	0.1488	0.22
17	94.0	2.6	1.6	0.8	0.9	2985.47	93.1%	90.2%	95.9%	23.08	0.1477	0.22
18	94.2	2.6	1.6	0.7	0.9	3164.69	93.3%	90.3%	95.9%	22.07	0.1417	0.21
19	94.2	2.6	1.6	0.6	0.9	3345.16	93.1%	90.3%	95.9%	22.14	0.1420	0.21
20	94.1	2.6	1.6	0.7	0.9	3524.34	93.2%	90.2%	95.9%	22.04	0.1412	0.21
21	94.0	2.6	1.7	0.8	0.9	3704.03	93.1%	90.3%	95.8%	21.79	0.1395	0.21
22	94.2	2.6	1.6	0.8	0.9	3880.92	93.5%	90.4%	96.1%	19.15	0.1235	0.18
23	94.2	2.6	1.7	0.7	0.9	4063.42	92.9%	90.4%	96.0%	19.66	0.1259	0.19
24	94.1	2.5	1.7	0.8	0.9	4241.97	93.1%	90.5%	96.0%	19.67	0.1264	0.19
25	94.1	2.6	1.7	0.7	0.9	4422.04	93.0%	90.4%	95.9%	18.72	0.1200	0.18
26	94.0	2.6	1.7	0.7	0.9	4600.89	92.8%	90.2%	96.0%	17.98	0.1149	0.17
27	93.9	2.6	1.7	0.9	0.9	4780.60	92.9%	90.1%	95.9%	18.03	0.1151	0.17
28	94.0	2.6	1.7	0.8	0.9	4959.58	93.0%	90.3%	95.9%	17.32	0.1110	0.16
29												
30												
31												
32												
33												
34												
35												
36												
37												
38												
39												
40												
41	94.6	2.3	1.7	0.7	0.8	7427.70	93.1%	91.4%	96.5%	22.79	0.1489	0.22
42	94.4	2.3	1.7	0.8	0.8	7605.58	92.8%	91.2%	96.3%	20.44	0.1325	0.20
43	94.4	2.3	1.7	0.7	0.8	7784.24	93.0%	91.2%	96.3%	19.27	0.1252	0.19
44	94.4	2.3	1.7	0.7	0.8	7963.69	93.1%	91.1%	96.2%	18.13	0.1176	0.17
45	94.4	2.4	1.6	0.7	0.8	8143.28	93.2%	91.0%	96.2%	17.07	0.1106	0.16
46	94.4	2.4	1.6	0.7	0.9	8322.70	93.1%	90.9%	96.1%	16.95	0.1097	0.16
47	94.2	2.5	1.7	0.8	0.9	8502.48	93.1%	90.7%	96.1%	16.64	0.1075	0.16
48	94.5	2.4	1.6	0.7	0.8	8681.62	93.5%	90.9%	96.3%	15.53	0.1010	0.15
49	94.5	2.4	1.6	0.7	0.8	8861.38	93.5%	91.0%	96.2%	14.94	0.0972	0.14
50	94.5	2.4	1.6	0.7	0.9	9040.95	93.5%	90.9%	96.2%	15.05	0.0977	0.14
51	94.3	2.4	1.6	0.9	0.9	9220.62	93.4%	90.9%	96.1%	15.14	0.0983	0.15
52	94.4	2.4	1.6	0.7	0.9	9400.67	93.2%	90.8%	96.1%	14.61	0.0944	0.14
53	94.3	2.4	1.6	0.7	0.9	9580.60	93.3%	90.8%	96.0%	14.40	0.0931	0.14
54	94.4	2.4	1.6	0.7	0.9	9760.06	93.3%	90.9%	96.1%	14.04	0.0910	0.13
55	94.3	2.5	1.6	0.7	0.9	9940.04	93.2%	90.7%	96.0%	13.73	0.0886	0.13
56	94.3	2.4	1.6	0.8	0.9	10119.21	93.3%	90.9%	96.0%	13.93	0.0902	0.13
57	94.3	2.4	1.6	0.8	0.9	10298.99	93.4%	90.9%	96.1%	13.38	0.0868	0.13
58	94.4	2.4	1.6	0.7	0.9	10479.05	93.3%	91.0%	96.0%	13.06	0.0845	0.13
59	94.0	2.4	1.6	0.9	0.9	10658.83	93.1%	90.8%	95.8%	13.50	0.0870	0.13
60	95.2	1.6	1.6	0.6	1.0	10838.39	93.5%	93.9%	95.3%	12.16	0.0809	0.12
61	93.7	2.6	1.8	1.0	0.9	11018.20	92.4%	90.3%	95.7%	12.97	0.0824	0.12
62	93.8	2.7	1.8	0.8	0.9	11198.37	92.3%	90.0%	95.8%	11.61	0.0735	0.11
63	93.4	2.9	2.0	0.8	0.9	11378.09	91.6%	89.3%	95.7%	11.95	0.0743	0.11
64	93.4	2.8	2.0	0.8	0.9	11557.71	91.7%	89.5%	95.7%	11.31	0.0707	0.10
65	93.6	2.7	1.9	0.8	0.9	11737.37	91.9%	89.7%	95.7%	11.43	0.0717	0.11
66	94.0	2.5	1.7	0.8	0.9	11917.75	92.8%	90.6%	95.7%	11.58	0.0741	0.11
67	94.2	2.4	1.7	0.8	0.9	12096.91	93.1%	90.7%	95.8%	11.25	0.0724	0.11
68	94.3	2.4	1.6	0.8	0.9	12276.89	93.2%	90.9%	95.9%	10.71	0.0692	0.10
69	94.1	2.5	1.7	0.7	0.9	12456.68	92.9%	90.5%	95.8%	10.75	0.0689	0.10
70	94.2	2.4	1.7	0.8	0.9	12636.65	93.0%	90.8%	95.8%	10.40	0.0668	0.10
71	94.0	2.5	1.7	0.8	0.9	12816.50	92.8%	90.5%	95.7%	10.78	0.0689	0.10
72	94.1	2.5	1.7	0.8	0.9	12996.12	93.0%	90.6%	95.8%	10.18	0.0653	0.10
73	93.8	2.6	1.8	1.0	0.7	13177.06	92.3%	90.4%	96.6%	11.24	0.0720	0.11
74	94.1	2.6	1.8	0.8	0.8	13356.57	92.6%	90.4%	96.5%	10.18	0.0654	0.10
75	94.0	2.5	1.7	1.0	0.8	13536.34	92.7%	90.5%	96.5%	10.19	0.0656	0.10


Average Reaction Efficiencies ECM255061C300 & Engelhard Escat 326
Average Reaction Efficiencies
ECM255061C300 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
70
80
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM255061C300 & Engelhard Escat 326
Average Reformate Composition
ECM255061C300 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
10
20
30
40
50
60
70
80
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent ECM255061C300 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM255061C300 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
Cycle

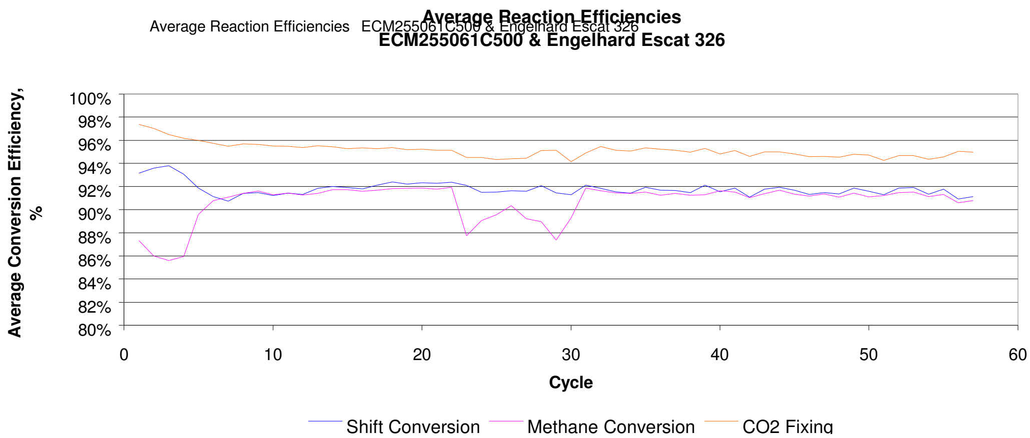
CO_2 Sorption Catalyst	ECM255061C500
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	*CaO/Al203 (90/10)
Binder	15%Al203
Batch No.	PCB954103A-1
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	500

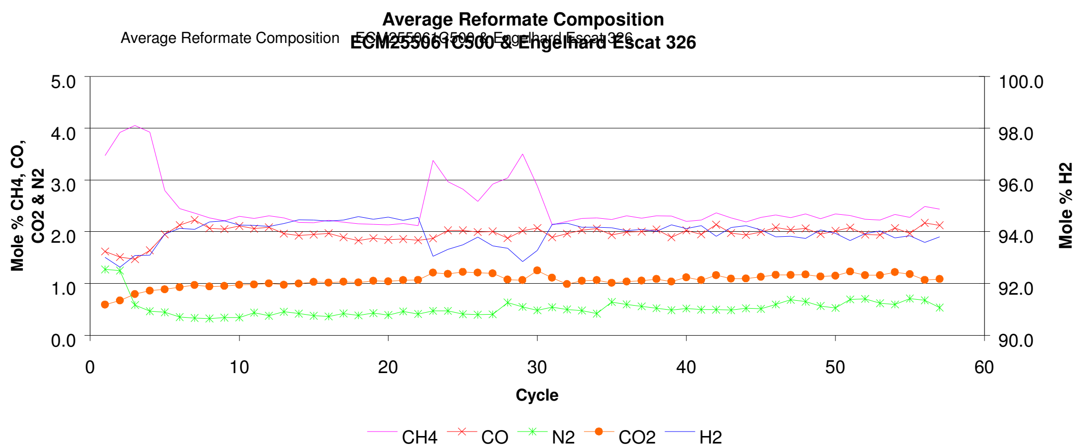
Wt. CO2 extrudate, g	31.85
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	1.0
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	36.35
Total Bed Vol., ml	40.0

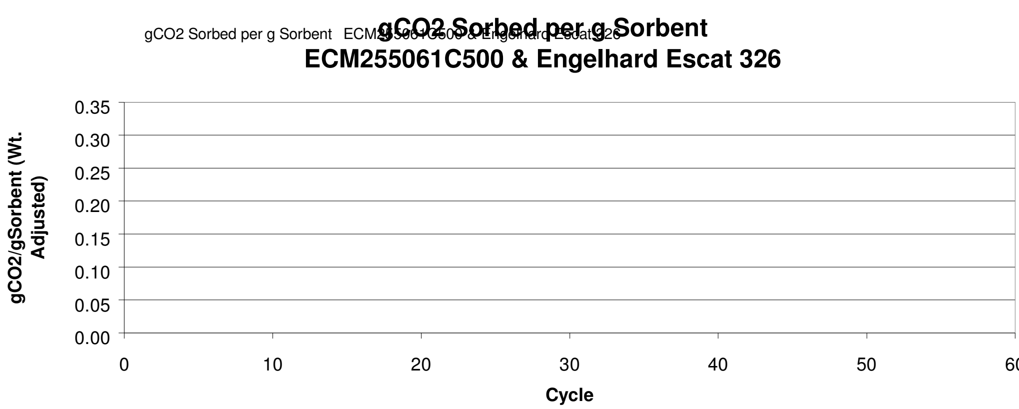
Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	93.0	3.5	1.6	1.3	0.6	374.04	93.1%	87.3%	97.4%	2.68	0.0170	0.02
2	92.6	3.9	1.5	1.2	0.7	555.00	93.6%	86.0%	97.0%	4.82	0.0302	0.04
3	93.1	4.1	1.5	0.6	0.8	742.75	93.8%	85.6%	96.5%	12.40	0.0770	0.11
4	93.1	3.9	1.6	0.5	0.9	939.87	93.1%	86.0%	96.2%	29.79	0.1839	0.26
5	93.9	2.8	1.9	0.4	0.9	1119.96	91.9%	89.6%	96.0%	29.74	0.1885	0.27
6	94.1	2.4	2.1	0.3	0.9	1300.22	91.1%	90.8%	95.7%	29.81	0.1895	0.27
7	94.1	2.4	2.2	0.3	1.0	1480.25	90.7%	91.1%	95.5%	29.26	0.1854	0.26
8	94.4	2.3	2.1	0.3	0.9	1657.57	91.4%	91.4%	95.7%	26.98	0.1731	0.24
9	94.4	2.2	2.0	0.3	1.0	1836.88	91.5%	91.6%	95.6%	26.18	0.1684	0.24
10	94.3	2.3	2.1	0.3	1.0	2016.83	91.2%	91.3%	95.5%	26.16	0.1670	0.23
11	94.2	2.3	2.1	0.4	1.0	2195.90	91.4%	91.4%	95.5%	25.54	0.1637	0.23
12	94.2	2.3	2.1	0.4	1.0	2375.69	91.3%	91.3%	95.4%	25.41	0.1621	0.23
13	94.3	2.3	2.0	0.5	1.0	2554.48	91.8%	91.4%	95.5%	24.41	0.1571	0.22
14	94.5	2.2	1.9	0.4	1.0	2734.24	92.0%	91.7%	95.4%	24.43	0.1580	0.22
15	94.5	2.2	1.9	0.4	1.0	2914.47	91.9%	91.7%	95.3%	23.92	0.1543	0.22
16	94.4	2.2	2.0	0.4	1.0	3093.71	91.8%	91.6%	95.3%	23.45	0.1509	0.21
17	94.4	2.2	1.9	0.4	1.0	3273.06	92.1%	91.7%	95.3%	22.77	0.1471	0.21
18	94.6	2.2	1.8	0.4	1.0	3452.43	92.4%	91.8%	95.4%	22.21	0.1442	0.20
19	94.5	2.1	1.9	0.4	1.0	3632.49	92.2%	91.8%	95.2%	22.22	0.1438	0.20
20	94.6	2.1	1.8	0.4	1.0	3812.26	92.3%	91.9%	95.2%	21.15	0.1372	0.19
21	94.4	2.2	1.9	0.5	1.1	3991.22	92.3%	91.8%	95.1%	21.22	0.1372	0.19
22	94.6	2.1	1.8	0.4	1.1	4170.97	92.4%	91.9%	95.1%	20.21	0.1311	0.18
23	93.1	3.4	1.9	0.5	1.2	4351.93	92.1%	87.7%	94.5%	21.23	0.1300	0.18
24	93.3	3.0	2.0	0.5	1.2	4532.28	91.5%	89.0%	94.5%	21.07	0.1300	0.18
25	93.5	2.8	2.0	0.4	1.2	4711.45	91.5%	89.6%	94.3%	20.47	0.1269	0.18
26	93.8	2.6	2.0	0.4	1.2	4890.01	91.6%	90.3%	94.4%	18.25	0.1145	0.16
27	93.5	2.9	2.0	0.4	1.2	5068.90	91.6%	89.2%	94.5%	17.47	0.1082	0.15
28	93.4	3.0	1.9	0.6	1.1	5247.21	92.1%	89.0%	95.1%	17.13	0.1072	0.15
29	92.8	3.5	2.0	0.5	1.1	5427.95	91.5%	87.4%	95.1%	16.26	0.0992	0.14
30	93.3	2.9	2.1	0.5	1.3	5607.98	91.3%	89.3%	94.1%	17.04	0.1050	0.15
31	94.3	2.1	1.9	0.5	1.1	5785.78	92.1%	91.9%	94.9%	15.23	0.0982	0.14
32	94.3	2.2	2.0	0.5	1.0	5966.06	91.8%	91.6%	95.5%	15.66	0.1010	0.14
33	94.2	2.3	2.0	0.5	1.0	6146.22	91.5%	91.4%	95.1%	15.25	0.0975	0.14
34	94.2	2.3	2.1	0.4	1.1	6325.95	91.4%	91.4%	95.1%	15.14	0.0966	0.14
35	94.2	2.2	1.9	0.6	1.0	6504.80	91.9%	91.5%	95.3%	14.61	0.0941	0.13
36	94.0	2.3	2.0	0.6	1.0	6684.55	91.7%	91.2%	95.2%	14.56	0.0931	0.13
37	94.1	2.3	2.0	0.6	1.1	6864.63	91.7%	91.4%	95.1%	14.12	0.0904	0.13
38	94.0	2.3	2.0	0.5	1.1	7044.70	91.5%	91.2%	95.0%	13.54	0.0862	0.12
39	94.3	2.3	1.9	0.5	1.0	7223.35	92.1%	91.3%	95.3%	12.38	0.0796	0.11
40	94.1	2.2	2.0	0.5	1.1	7404.22	91.6%	91.6%	94.8%	13.12	0.0838	0.12
41	94.2	2.2	1.9	0.5	1.1	7583.24	91.9%	91.5%	95.1%	12.49	0.0802	0.11
42	93.8	2.4	2.1	0.5	1.2	7763.78	91.1%	91.0%	94.6%	12.52	0.0788	0.11
43	94.2	2.3	2.0	0.5	1.1	7942.80	91.8%	91.4%	95.0%	12.00	0.0767	0.11
44	94.2	2.2	1.9	0.5	1.1	8122.61	91.9%	91.7%	95.0%	11.69	0.0751	0.11
45	94.1	2.3	2.0	0.5	1.1	8302.19	91.7%	91.3%	94.8%	11.67	0.0744	0.10
46	93.8	2.3	2.1	0.6	1.2	8482.14	91.3%	91.2%	94.6%	11.52	0.0728	0.10
47	93.8	2.3	2.0	0.7	1.2	8662.14	91.5%	91.4%	94.6%	11.45	0.0727	0.10
48	93.7	2.3	2.1	0.7	1.2	8841.80	91.4%	91.1%	94.5%	11.40	0.0720	0.10
49	94.1	2.3	2.0	0.6	1.1	9021.49	91.9%	91.4%	94.8%	10.31	0.0659	0.09
50	93.9	2.3	2.0	0.5	1.1	9201.22	91.6%	91.1%	94.7%	10.22	0.0648	0.09
51	93.7	2.3	2.1	0.7	1.2	9381.43	91.3%	91.2%	94.3%	10.86	0.0685	0.10
52	93.9	2.2	1.9	0.7	1.2	9560.46	91.9%	91.5%	94.7%	10.29	0.0657	0.09
53	94.0	2.2	1.9	0.6	1.2	9740.54	91.9%	91.5%	94.7%	9.79	0.0626	0.09
54	93.8	2.3	2.1	0.6	1.2	9921.12	91.3%	91.1%	94.3%	9.79	0.0617	0.09
55	93.8	2.3	2.0	0.7	1.2	10100.20	91.8%	91.3%	94.6%	9.82	0.0625	0.09
56	93.6	2.5	2.2	0.7	1.1	10280.73	90.9%	90.6%	95.0%	9.76	0.0613	0.09
57	93.8	2.4	2.1	0.5	1.1	10460.25	91.1%	90.8%	95.0%	9.22	0.0582	0.08

Cycles 23-30: Preheater Failure


Average Reaction Efficiencies ECM255061C500 & Engelhard Escat 326
Average Reaction Efficiencies
ECM255061C500 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM255061C500 & Engelhard Escat 326
Average Reformate Composition
ECM255061C500 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0
10
20
30
40
50
60
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent ECM255061C500 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM255061C500 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
Cycle

CO_2 Sorption Catalyst	ECM255061C750
Reforming Catalyst: 0.5% rhodium o	Engelhard Escat 326
Composition CO_2 sorb	*CaO/Al203 (90/10)
Binder	15%Al203
Batch No.	PCB954103A-1
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

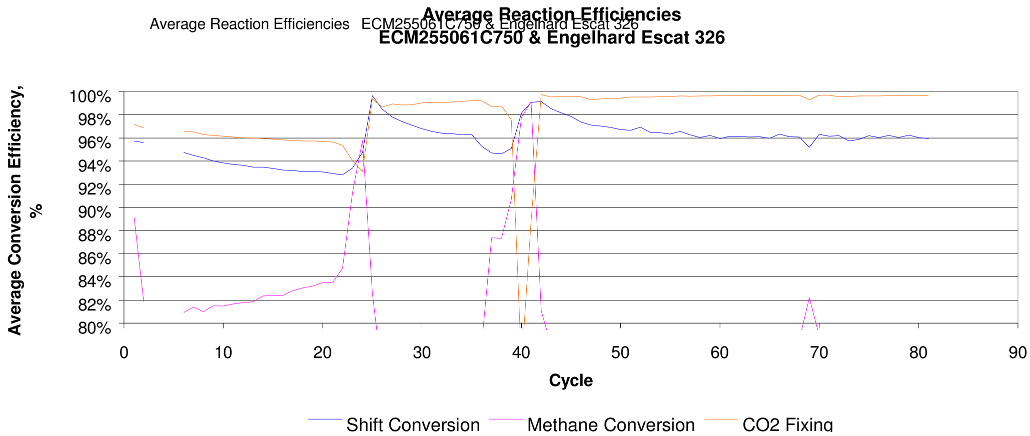
Wt. CO2 extrudate, g	27.96
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.9
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	32.46
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

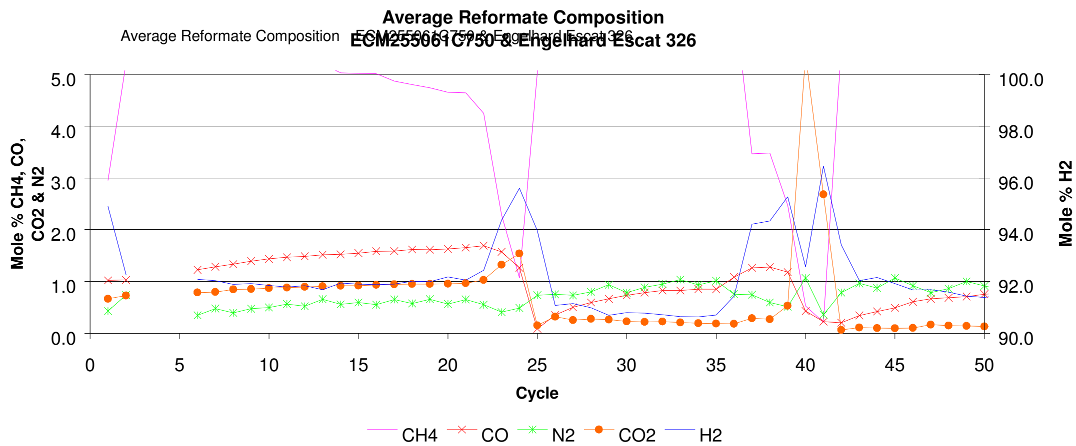
Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	94.9	3.0	1.0	0.4	0.7	264.43	95.7%	89.1%	97.2%	29.70	0.0038	0.27
2	92.3	5.2	1.0	0.7	0.7	431.64	95.6%	81.8%	96.9%	16.97	0.0035	0.14
3												
4												
5												
6	92.1	5.5	1.2	0.3	0.8	1149.23	94.7%	80.9%	96.6%	14.11	0.0034	0.11
7	92.0	5.4	1.3	0.5	0.8	1328.54	94.5%	81.4%	96.5%	14.24	0.0034	0.11
8	91.9	5.5	1.3	0.4	0.8	1509.92	94.3%	81.0%	96.3%	14.33	0.0034	0.11
9	91.9	5.3	1.4	0.5	0.9	1689.03	94.0%	81.5%	96.2%	14.45	0.0034	0.12
10	91.8	5.3	1.4	0.5	0.9	1870.07	93.8%	81.5%	96.2%	15.26	0.0034	0.12
11	91.8	5.3	1.5	0.6	0.9	2050.19	93.7%	81.7%	96.1%	15.65	0.0034	0.12
12	91.8	5.2	1.5	0.5	0.9	2230.39	93.6%	81.8%	96.0%	15.01	0.0034	0.12
13	91.7	5.2	1.5	0.7	0.9	2409.47	93.5%	81.9%	96.0%	14.44	0.0034	0.11
14	91.9	5.0	1.5	0.6	0.9	2590.05	93.5%	82.4%	95.9%	14.99	0.0034	0.12
15	91.9	5.0	1.5	0.6	0.9	2770.65	93.4%	82.4%	95.9%	15.78	0.0034	0.13
16	91.9	5.0	1.6	0.6	0.9	2950.69	93.2%	82.4%	95.8%	15.77	0.0034	0.13
17	91.9	4.9	1.6	0.7	0.9	3130.53	93.2%	82.8%	95.8%	15.73	0.0034	0.13
18	92.0	4.8	1.6	0.6	1.0	3310.46	93.1%	83.0%	95.7%	15.63	0.0034	0.13
19	92.0	4.7	1.6	0.7	1.0	3490.38	93.1%	83.2%	95.7%	15.69	0.0034	0.13
20	92.2	4.7	1.6	0.6	1.0	3669.70	93.1%	83.5%	95.7%	15.05	0.0034	0.12
21	92.1	4.6	1.7	0.7	1.0	3850.32	92.9%	83.5%	95.7%	15.71	0.0034	0.13
22	92.4	4.2	1.7	0.6	1.0	4032.18	92.8%	84.7%	95.4%	17.61	0.0034	0.14
23	94.4	2.3	1.6	0.4	1.3	4214.07	93.4%	91.3%	94.0%	19.58	0.0037	0.17
24	95.6	1.1	1.3	0.5	1.5	4393.16	94.7%	95.8%	93.1%	19.64	0.0039	0.18
25	94.0	5.0	0.1	0.7	0.2	4570.82	99.6%	82.6%	99.4%	14.54	0.0037	0.13
26	91.1	7.5	0.3	0.8	0.3	4925.17	98.5%	75.4%	98.7%	8.82	0.0033	0.07
27	91.1	7.3	0.5	0.7	0.3	5106.02	97.8%	75.8%	98.9%	9.06	0.0033	0.07
28	91.0	7.3	0.6	0.8	0.3	5283.64	97.4%	75.8%	98.8%	7.72	0.0033	0.06
29	90.7	7.4	0.7	0.9	0.3	5462.50	97.1%	75.5%	98.9%	6.43	0.0033	0.05
30	90.8	7.4	0.7	0.8	0.2	5642.57	96.8%	75.5%	99.0%	6.41	0.0033	0.05
31	90.8	7.3	0.8	0.9	0.2	5822.71	96.6%	75.8%	99.1%	6.27	0.0033	0.05
32	90.7	7.2	0.8	1.0	0.2	6001.34	96.4%	76.0%	99.0%	5.09	0.0033	0.04
33	90.6	7.3	0.8	1.0	0.2	6181.66	96.4%	75.9%	99.1%	5.65	0.0033	0.04
34	90.6	7.4	0.9	0.9	0.2	6362.06	96.3%	75.7%	99.2%	6.27	0.0033	0.05
35	90.7	7.2	0.9	1.0	0.2	6541.81	96.3%	76.0%	99.2%	6.29	0.0033	0.05
36	91.4	6.5	1.1	0.8	0.2	6726.08	95.3%	78.0%	99.2%	9.50	0.0034	0.08
37	94.2	3.5	1.3	0.7	0.3	6907.08	94.7%	87.4%	98.7%	13.27	0.0037	0.12
38	94.3	3.5	1.3	0.6	0.3	7088.05	94.6%	87.3%	98.8%	13.31	0.0037	0.12
39	95.3	2.5	1.2	0.5	0.5	7267.29	95.1%	90.7%	97.6%	12.74	0.0038	0.12
40	92.6	0.5	0.4	1.1	5.4	7438.15	98.2%	97.8%	76.4%	5.44	0.0033	0.04
41	96.5	0.2	0.2	0.4	2.7	7544.44	99.1%	99.1%	88.8%	0.00	0.0040	0.00
42	93.4	5.5	0.2	0.8	0.1	7806.10	99.1%	81.1%	99.7%	11.48	0.0037	0.10
43	92.0	6.5	0.3	1.0	0.1	7985.13	98.5%	78.1%	99.5%	10.70	0.0035	0.09
44	92.2	6.4	0.4	0.9	0.1	8164.91	98.2%	78.3%	99.6%	9.53	0.0035	0.08
45	91.9	6.4	0.5	1.1	0.1	8344.64	97.9%	78.4%	99.6%	9.49	0.0035	0.08
46	91.7	6.7	0.6	0.9	0.1	8525.06	97.4%	77.6%	99.6%	10.12	0.0034	0.08
47	91.7	6.7	0.7	0.8	0.2	8705.49	97.1%	77.6%	99.3%	9.52	0.0034	0.08
48	91.6	6.7	0.7	0.9	0.1	8884.80	97.0%	77.6%	99.4%	8.82	0.0034	0.07
49	91.4	6.7	0.7	1.0	0.1	9064.42	96.9%	77.6%	99.4%	8.85	0.0034	0.07
50	91.4	6.8	0.8	0.9	0.1	9244.19	96.7%	77.3%	99.5%	8.85	0.0034	0.07
51	91.5	6.8	0.8	0.8	0.1	9424.46	96.6%	77.4%	99.5%	8.17	0.0034	0.07
52	91.7	6.6	0.7	0.8	0.1	9602.93	96.9%	77.8%	99.5%	6.94	0.0034	0.06
53	91.4	6.7	0.8	1.0	0.1	9783.88	96.5%	77.5%	99.5%	8.22	0.0034	0.07
54	91.3	6.6	0.8	1.1	0.1	9963.73	96.5%	77.9%	99.6%	8.15	0.0034	0.07
55	91.4	6.6	0.8	1.0	0.1	10143.37	96.3%	77.7%	99.6%	8.19	0.0034	0.07
56	91.3	6.8	0.8	1.0	0.1	10323.20	96.6%	77.2%	99.6%	6.95	0.0034	0.06
57	91.6	6.5	0.9	0.8	0.1	10503.64	96.3%	78.0%	99.6%	7.59	0.0034	0.06
58	91.5	6.5	0.9	1.0	0.1	10683.92	96.0%	78.1%	99.6%	8.28	0.0034	0.07
59	91.6	6.5	0.9	1.0	0.1	10863.06	96.2%	78.1%	99.6%	7.59	0.0034	0.06
60	91.5	6.5	0.9	0.9	0.1	11043.88	96.0%	78.1%	99.6%	7.57	0.0034	0.06
61	91.4	6.5	0.9	1.1	0.1	11223.09	96.1%	78.1%	99.6%	8.23	0.0034	0.07
62	91.7	6.4	0.9	0.9	0.1	11403.28	96.1%	78.5%	99.6%	7.54	0.0034	0.06
63	91.7	6.4	0.9	0.9	0.1	11583.50	96.1%	78.5%	99.7%	6.94	0.0034	0.06
64	91.7	6.4	0.9	0.9	0.1	11763.04	96.1%	78.4%	99.7%	6.94	0.0034	0.06
65	91.6	6.3	0.9	1.1	0.1	11943.32	96.0%	78.6%	99.7%	7.62	0.0034	0.06
66	91.8	6.3	0.8	1.0	0.1	12122.34	96.3%	78.7%	99.7%	6.93	0.0035	0.06
67	91.8	6.3	0.9	0.9	0.1	12303.19	96.1%	78.6%	99.7%	6.90	0.0034	0.06
68	91.8	6.3	0.9	0.9	0.1	12482.93	96.1%	78.6%	99.7%	7.00	0.0034	0.06
69	92.6	5.1	1.1	1.0	0.2	12663.50	95.2%	82.2%	99.3%	8.21	0.0035	0.07
70	91.8	6.2	0.9	1.0	0.1	12842.11	96.3%	78.9%	99.7%	6.95	0.0035	0.06
71	91.8	6.2	0.9	0.9	0.1	13022.92	96.1%	78.9%	99.7%	7.02	0.0035	0.06
72	91.9	6.2	0.9	1.0	0.1	13202.83	96.2%	79.1%	99.6%	6.97	0.0035	0.06
73	91.7	6.3	1.0	0.9	0.1	13383.16	95.7%	78.8%	99.6%	7.57	0.0034	0.06
74	91.7	6.2	1.0	1.0	0.1	13563.19	95.9%	78.9%	99.6%	6.92	0.0034	0.06
75	91.9	6.2	0.9	0.9	0.1	13742.45	96.2%	79.0%	99.6%	6.38	0.0035	0.05
76	91.7	6.2	0.9	1.1	0.1	13922.64	96.0%	79.0%	99.6%	6.93	0.0035	0.06
77	91.7	6.2	0.9	1.1	0.1	14101.94	96.2%	79.0%	99.6%	6.97	0.0035	0.06
78	91.8	6.2	0.9	1.0	0.1	14282.66	96.0%	78.9%	99.6%	6.89	0.0035	0.06
79	91.7	6.1	0.9	1.2	0.1	14461.71	96.2%	79.1%	99.6%	6.93	0.0035	0.06
80	91.7	6.2	0.9	1.1	0.1	14642.38	96.0%	79.1%	99.7%	6.91	0.0035	0.06
81	91.9	6.1	0.9	0.9	0.1	14822.82	95.9%	79.1%	99.7%	6.40	0.0035	0.05
82	91.9	6.2	0.9	0.9	0.1	15002.53	96.0%	78.9%	99.7%	6.47	0.0034	0.05
83	91.6	6.3	0.9	1.1	0.1	15182.31	96.0%	78.6%	99.7%	6.43	0.0034	0.05
84	91.7	6.3	0.9	1.0	0.1	15362.16	96.0%	78.6%	99.7%	6.49	0.0034	0.05

Cycles 2 - 40: NI Temperature Control Erratic

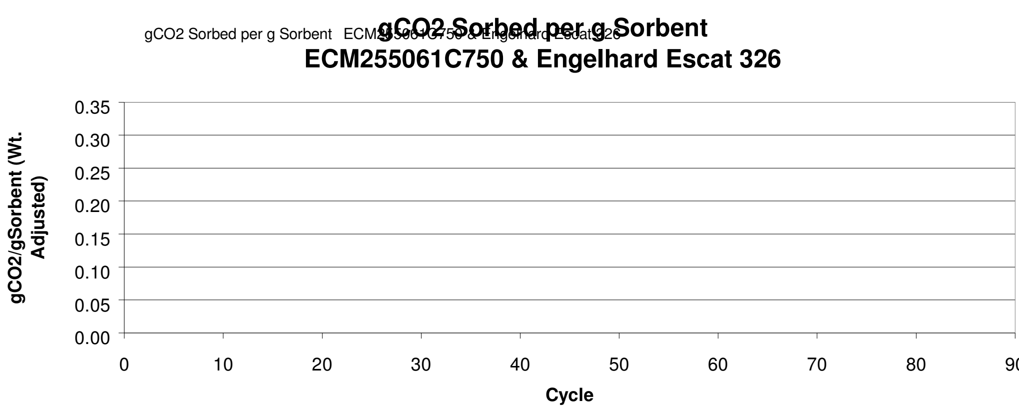
Average Reaction Efficiencies ECM255061C750 & Engelhard Escat 326



Average Reformate Composition ECM255061C750 & Engelhard Escat 326

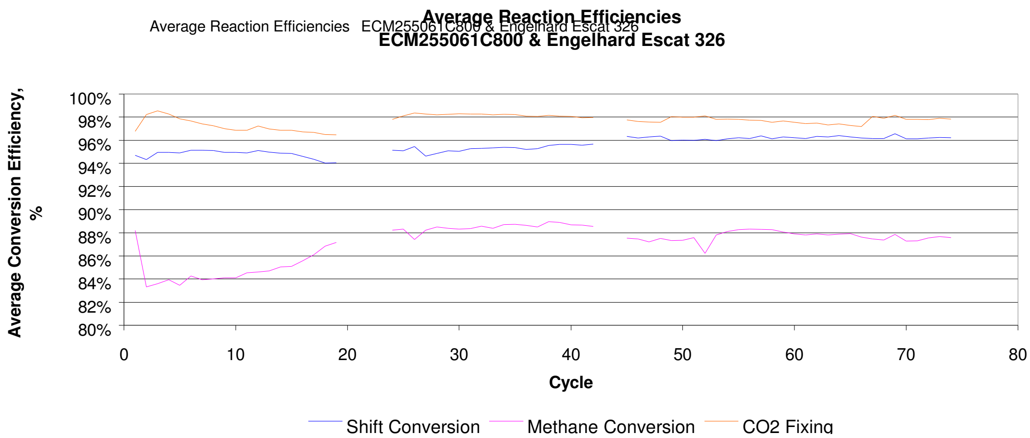


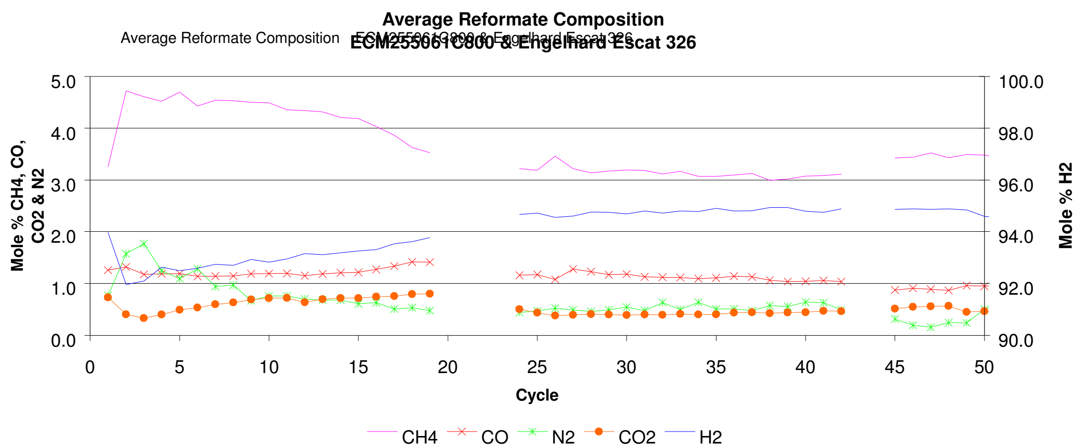
gCO2 Sorbed per g Sorbent ECM255061C750 & Engelhard Escat 326

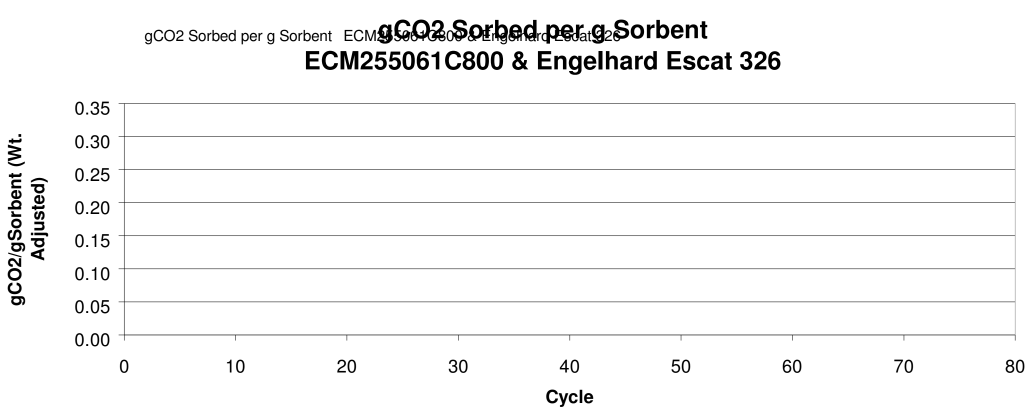


CO_2 Sorption Catalyst	ECM255061C800	Wt. CO2 extrudate, g	24.82	Reactor	R1
Reforming Catalyst: 0.5% rhodium on	Engelhard Escat 326	Vol. CO2 extrudate, cc	32.5	S/C	3
Composition CO_2 sorb	CaO/Al203 (90/10)	Density CO2, g/cc	0.8	GHSV, hr-1	390
Binder	15%Al203	Wt. SMR Cat., g	4.5	Reforming, °C	600
Batch No.	PCB954103A-1	Vol. SMR Cat., cc	7.5	Calcination, °C	800
Extruded by	CSMP	Density SMR, g/cc	0.6	Pressure, atm.	1
Oven Atmosphere	Air	Total Bed Wt., g	29.32		
Calcined, C	800	Total Bed Vol., ml	40.0		

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	94.0	3.2	1.3	0.8	0.7	956.67	94.7%	88.2%	96.8%	14.86	0.1239	0.13
2	92.0	4.7	1.3	1.6	0.4	1094.67	94.3%	83.3%	98.2%	3.11	0.0248	0.03
3	92.1	4.6	1.2	1.8	0.3	1274.40	95.0%	83.6%	98.6%	2.50	0.0202	0.02
4	92.6	4.5	1.2	1.2	0.4	1454.84	94.9%	84.0%	98.3%	3.14	0.0253	0.03
5	92.5	4.7	1.2	1.1	0.5	1636.36	94.9%	83.5%	97.9%	4.47	0.0357	0.04
6	92.6	4.4	1.1	1.3	0.5	1816.99	95.1%	84.3%	97.7%	5.10	0.0412	0.04
7	92.7	4.5	1.1	0.9	0.6	1998.28	95.1%	84.0%	97.4%	6.41	0.0514	0.05
8	92.7	4.5	1.1	1.0	0.6	2179.64	95.1%	84.0%	97.3%	7.68	0.0614	0.06
9	92.9	4.5	1.2	0.7	0.7	2361.19	94.9%	84.1%	97.0%	9.00	0.0717	0.08
10	92.8	4.5	1.2	0.8	0.7	2541.28	94.9%	84.1%	96.9%	8.76	0.0698	0.07
11	93.0	4.4	1.2	0.8	0.7	2723.49	94.9%	84.6%	96.9%	12.00	0.0960	0.10
12	93.2	4.3	1.2	0.7	0.6	2906.33	95.1%	84.6%	97.2%	14.42	0.1162	0.12
13	93.1	4.3	1.2	0.7	0.7	3088.60	95.0%	84.7%	97.0%	16.32	0.1310	0.14
14	93.2	4.2	1.2	0.7	0.7	3270.52	94.9%	85.0%	96.9%	18.97	0.1527	0.16
15	93.3	4.2	1.2	0.6	0.7	3454.16	94.8%	85.1%	96.9%	22.06	0.1776	0.19
16	93.3	4.0	1.3	0.6	0.7	3635.35	94.6%	85.6%	96.7%	23.99	0.1935	0.20
17	93.5	3.9	1.3	0.5	0.8	3817.34	94.4%	86.1%	96.7%	25.22	0.2040	0.21
18	93.6	3.6	1.4	0.5	0.8	3997.53	94.0%	86.9%	96.5%	25.96	0.2107	0.22
19	93.8	3.5	1.4	0.5	0.8	4178.23	94.0%	87.2%	96.5%	25.81	0.2103	0.22
20												
21												
22												
23												
24	94.7	3.2	1.2	0.4	0.5	5077.91	95.1%	88.2%	97.8%	25.22	0.2133	0.22
25	94.7	3.2	1.2	0.5	0.4	5256.83	95.1%	88.3%	98.1%	24.69	0.2096	0.22
26	94.5	3.5	1.1	0.5	0.4	5436.88	95.5%	87.4%	98.3%	22.86	0.1932	0.20
27	94.6	3.2	1.3	0.5	0.4	5616.90	94.6%	88.2%	98.3%	24.69	0.2087	0.22
28	94.8	3.1	1.2	0.5	0.4	5796.34	94.8%	88.5%	98.2%	23.38	0.1987	0.21
29	94.7	3.2	1.2	0.5	0.4	5975.72	95.1%	88.4%	98.2%	23.38	0.1989	0.21
30	94.7	3.2	1.2	0.5	0.4	6155.43	95.0%	88.3%	98.3%	23.44	0.1994	0.21
31	94.8	3.2	1.1	0.5	0.4	6334.71	95.3%	88.4%	98.3%	22.13	0.1886	0.20
32	94.7	3.1	1.1	0.6	0.4	6513.95	95.3%	88.6%	98.3%	22.16	0.1894	0.20
33	94.8	3.2	1.1	0.5	0.4	6693.93	95.3%	88.4%	98.2%	21.51	0.1834	0.19
34	94.8	3.1	1.1	0.6	0.4	6873.24	95.4%	88.7%	98.2%	21.48	0.1840	0.19
35	94.9	3.1	1.1	0.5	0.4	7053.02	95.4%	88.7%	98.2%	20.87	0.1788	0.19
36	94.8	3.1	1.1	0.5	0.4	7233.46	95.2%	88.6%	98.1%	20.85	0.1778	0.19
37	94.8	3.1	1.1	0.5	0.4	7413.46	95.3%	88.5%	98.1%	20.86	0.1778	0.19
38	94.9	3.0	1.1	0.6	0.4	7592.24	95.5%	89.0%	98.1%	20.27	0.1743	0.18
39	94.9	3.0	1.0	0.6	0.4	7772.20	95.7%	88.9%	98.1%	19.57	0.1681	0.18
40	94.8	3.1	1.0	0.6	0.4	7951.43	95.6%	88.7%	98.1%	19.66	0.1685	0.18
41	94.7	3.1	1.1	0.6	0.5	8131.79	95.6%	88.7%	97.9%	19.57	0.1674	0.18
42	94.9	3.1	1.0	0.5	0.5	8311.49	95.7%	88.6%	98.0%	18.95	0.1621	0.17
43												
44												
45	94.9	3.4	0.9	0.3	0.5	9030.14	96.3%	87.5%	97.8%	17.42	0.1480	0.16
46	94.9	3.4	0.9	0.2	0.5	9210.71	96.2%	87.5%	97.6%	16.42	0.1389	0.15
47	94.9	3.5	0.9	0.2	0.6	9390.30	96.3%	87.2%	97.6%	16.36	0.1381	0.15
48	94.9	3.4	0.9	0.2	0.6	9569.92	96.4%	87.5%	97.5%	16.42	0.1391	0.15
49	94.8	3.5	1.0	0.2	0.4	9750.13	96.0%	87.3%	98.0%	17.35	0.1469	0.15
50	94.6	3.5	0.9	0.5	0.5	9929.71	96.0%	87.4%	98.0%	16.87	0.1429	0.15
51	94.5	3.4	1.0	0.6	0.5	10108.77	96.0%	87.6%	98.0%	16.38	0.1390	0.15
52	94.3	3.9	0.9	0.4	0.4	10289.43	96.1%	86.2%	98.1%	15.31	0.1282	0.13
53	94.7	3.3	1.0	0.5	0.5	10468.61	96.0%	87.8%	97.8%	16.10	0.1367	0.14
54	94.9	3.3	0.9	0.4	0.5	10648.59	96.1%	88.1%	97.8%	14.74	0.1258	0.13
55	94.9	3.2	0.9	0.5	0.5	10828.36	96.2%	88.3%	97.8%	14.75	0.1262	0.13
56	94.9	3.2	0.9	0.4	0.5	11008.24	96.1%	88.3%	97.7%	14.73	0.1259	0.13
57	94.9	3.2	0.9	0.5	0.5	11187.78	96.4%	88.3%	97.7%	14.17	0.1213	0.13
58	94.9	3.2	0.9	0.4	0.6	11367.72	96.1%	88.3%	97.6%	14.09	0.1202	0.13
59	94.7	3.3	0.9	0.6	0.5	11547.24	96.3%	88.1%	97.7%	13.92	0.1187	0.12
60	94.7	3.3	0.9	0.5	0.6	11727.21	96.2%	87.9%	97.5%	13.92	0.1183	0.12
61	94.6	3.3	0.9	0.5	0.6	11907.20	96.2%	87.8%	97.4%	13.86	0.1175	0.12
62	94.8	3.3	0.9	0.5	0.6	12086.69	96.3%	87.9%	97.5%	13.29	0.1129	0.12
63	94.7	3.3	0.9	0.5	0.6	12266.83	96.3%	87.8%	97.3%	13.23	0.1122	0.12
64	94.8	3.3	0.9	0.4	0.6	12446.29	96.4%	87.9%	97.4%	12.62	0.1073	0.11
65	94.6	3.3	0.9	0.6	0.6	12626.64	96.3%	87.9%	97.3%	13.19	0.1119	0.12
66	94.5	3.4	0.9	0.5	0.6	12806.52	96.2%	87.6%	97.2%	13.24	0.1117	0.12
67	94.6	3.4	0.9	0.5	0.5	12986.59	96.2%	87.5%	98.1%	13.24	0.1124	0.12
68	94.6	3.5	0.9	0.5	0.5	13166.51	96.2%	87.4%	97.9%	13.19	0.1118	0.12
69	94.7	3.3	0.8	0.7	0.4	13345.56	96.6%	87.9%	98.2%	12.49	0.1071	0.11
70	94.5	3.5	0.9	0.5	0.5	13526.56	96.1%	87.3%	97.8%	12.70	0.1073	0.11
71	94.5	3.5	0.9	0.5	0.5	13706.31	96.1%	87.3%	97.8%	12.60	0.1065	0.11
72	94.5	3.4	0.9	0.6	0.5	13886.10	96.2%	87.6%	97.8%	12.58	0.1067	0.11
73	94.6	3.4	0.9	0.6	0.5	14065.77	96.2%	87.7%	97.9%	12.55	0.1067	0.11
74	94.7	3.4	0.9	0.5	0.5	14246.18	96.2%	87.6%	97.8%	11.93	0.1013	0.11


Average Reaction Efficiencies ECM255061C800 & Engelhard Escat 326
Average Reaction Efficiencies
ECM255061C800 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
70
80
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM255061C800 & Engelhard Escat 326
Average Reformate Composition
ECM255061C800 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
5
10
15
20
25
30
35
40
45
50
Cycle
CH4
CO
N2
CO2
H2

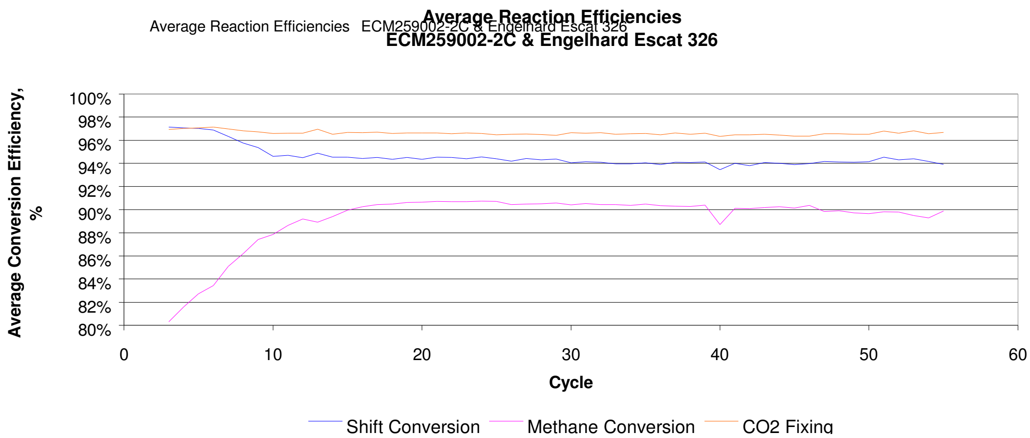

gCO2 Sorbed per g Sorbent ECM255061C800 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM255061C800 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
Cycle

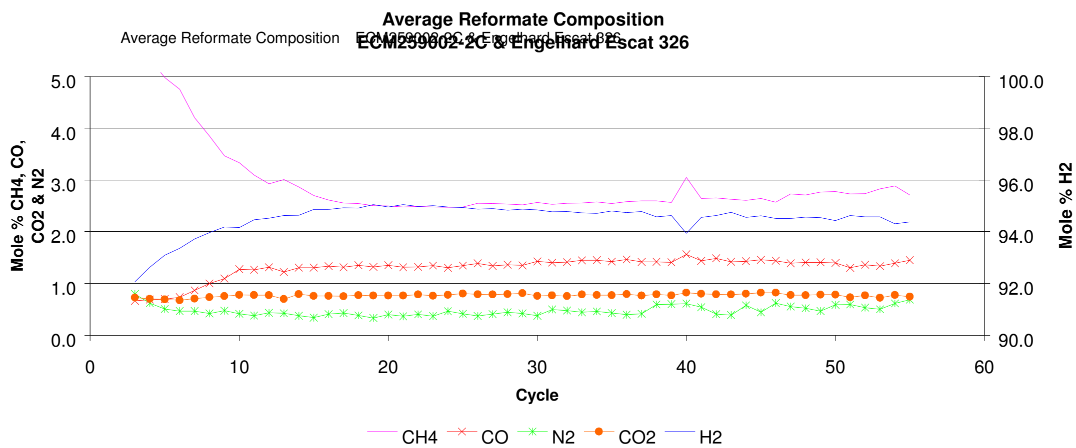
CO_2 Sorption Catalyst	ECM259002-2C
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/Al203 (90/10)
Binder	15%Al203
Batch No.	PCB290040C
Extruded by	CSMP
Oven Atmosphere	N2
Calcined, C	750

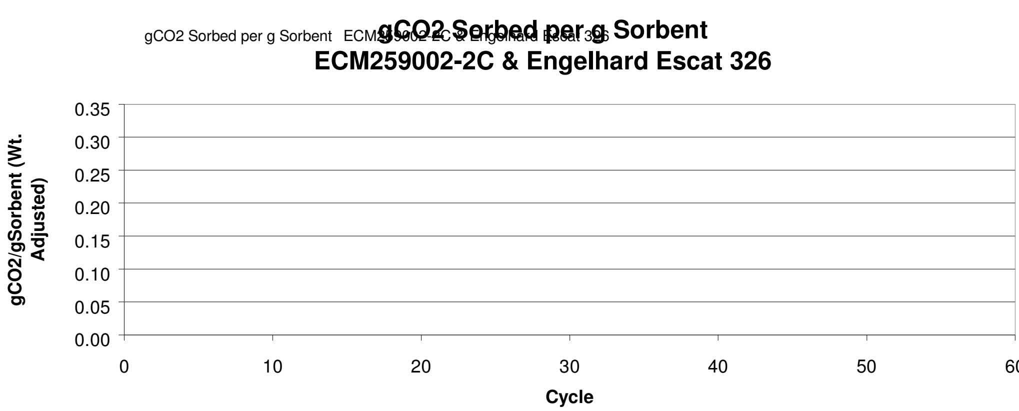
Wt. CO2 extrudate, g	27.73
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.9
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	32.23
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1												
2												
3	92.1	5.7	0.7	0.8	0.7	1013.23	97.1%	80.3%	96.9%	5.35	0.0372	0.05
4	92.6	5.3	0.7	0.6	0.7	1198.92	97.1%	81.6%	97.0%	10.71	0.0758	0.10
5	93.1	5.0	0.7	0.5	0.7	1384.62	97.0%	82.7%	97.1%	17.22	0.1235	0.16
6	93.4	4.8	0.7	0.5	0.7	1571.12	96.9%	83.4%	97.1%	23.22	0.1679	0.22
7	93.7	4.2	0.9	0.5	0.7	1753.79	96.3%	85.1%	97.0%	26.60	0.1948	0.25
8	94.0	3.8	1.0	0.4	0.7	1935.57	95.8%	86.2%	96.8%	27.83	0.2051	0.27
9	94.2	3.5	1.1	0.5	0.8	2114.88	95.4%	87.4%	96.7%	28.24	0.2100	0.27
10	94.2	3.3	1.3	0.4	0.8	2296.75	94.6%	87.9%	96.6%	29.30	0.2170	0.28
11	94.5	3.1	1.3	0.4	0.8	2475.46	94.7%	88.6%	96.6%	28.35	0.2119	0.28
12	94.5	2.9	1.3	0.4	0.8	2655.29	94.5%	89.2%	96.6%	28.29	0.2124	0.28
13	94.6	3.0	1.2	0.4	0.7	2835.81	94.9%	88.9%	96.9%	29.15	0.2198	0.29
14	94.6	2.9	1.3	0.4	0.8	3014.17	94.5%	89.4%	96.5%	26.67	0.2005	0.26
15	94.9	2.7	1.3	0.3	0.8	3193.97	94.5%	90.0%	96.7%	26.63	0.2019	0.26
16	94.9	2.6	1.3	0.4	0.8	3373.82	94.4%	90.3%	96.7%	26.80	0.2036	0.26
17	94.9	2.6	1.3	0.4	0.8	3553.35	94.5%	90.5%	96.7%	26.21	0.1998	0.26
18	94.9	2.5	1.4	0.4	0.8	3733.32	94.4%	90.5%	96.6%	26.20	0.1992	0.26
19	95.0	2.5	1.3	0.3	0.8	3913.28	94.5%	90.6%	96.6%	25.19	0.1922	0.25
20	95.0	2.5	1.4	0.4	0.8	4092.56	94.4%	90.6%	96.6%	25.59	0.1950	0.25
21	95.1	2.5	1.3	0.4	0.8	4272.45	94.5%	90.7%	96.6%	24.46	0.1869	0.24
22	95.0	2.5	1.3	0.4	0.8	4451.64	94.5%	90.7%	96.6%	24.54	0.1871	0.24
23	95.0	2.5	1.3	0.4	0.8	4631.96	94.4%	90.7%	96.6%	24.01	0.1832	0.24
24	95.0	2.5	1.3	0.5	0.8	4810.70	94.6%	90.7%	96.6%	24.03	0.1836	0.24
25	94.9	2.5	1.3	0.4	0.8	4990.91	94.4%	90.7%	96.5%	23.53	0.1792	0.23
26	94.9	2.6	1.4	0.4	0.8	5170.56	94.2%	90.5%	96.5%	23.47	0.1779	0.23
27	94.9	2.5	1.3	0.4	0.8	5350.07	94.4%	90.5%	96.5%	22.33	0.1698	0.22
28	94.8	2.5	1.4	0.4	0.8	5529.36	94.3%	90.5%	96.5%	22.40	0.1701	0.22
29	94.9	2.5	1.3	0.4	0.8	5708.95	94.4%	90.6%	96.4%	21.35	0.1622	0.21
30	94.8	2.6	1.4	0.4	0.8	5888.72	94.1%	90.4%	96.7%	21.26	0.1612	0.21
31	94.8	2.5	1.4	0.5	0.8	6067.94	94.2%	90.5%	96.6%	20.76	0.1576	0.20
32	94.8	2.5	1.4	0.5	0.8	6247.05	94.1%	90.5%	96.7%	20.09	0.1524	0.20
33	94.7	2.6	1.4	0.4	0.8	6427.06	94.0%	90.4%	96.5%	19.61	0.1483	0.19
34	94.7	2.6	1.4	0.5	0.8	6606.22	93.9%	90.4%	96.6%	19.11	0.1444	0.19
35	94.8	2.5	1.4	0.4	0.8	6785.80	94.1%	90.5%	96.6%	18.02	0.1366	0.18
36	94.7	2.6	1.5	0.4	0.8	6965.48	93.9%	90.3%	96.5%	17.94	0.1354	0.18
37	94.8	2.6	1.4	0.4	0.8	7145.00	94.1%	90.3%	96.6%	16.89	0.1279	0.17
38	94.6	2.6	1.4	0.6	0.8	7324.29	94.1%	90.3%	96.5%	16.86	0.1274	0.17
39	94.6	2.6	1.4	0.6	0.8	7503.41	94.1%	90.4%	96.6%	16.37	0.1241	0.16
40	93.9	3.1	1.6	0.6	0.8	7684.48	93.4%	88.7%	96.3%	16.83	0.1239	0.16
41	94.6	2.6	1.4	0.5	0.8	7862.99	94.0%	90.1%	96.5%	15.85	0.1194	0.16
42	94.6	2.7	1.5	0.4	0.8	8043.34	93.8%	90.1%	96.5%	15.12	0.1137	0.15
43	94.7	2.6	1.4	0.4	0.8	8222.40	94.1%	90.2%	96.5%	14.51	0.1095	0.14
44	94.6	2.6	1.4	0.6	0.8	8402.07	94.0%	90.2%	96.4%	14.52	0.1096	0.14
45	94.6	2.6	1.5	0.4	0.8	8582.07	93.9%	90.1%	96.4%	14.14	0.1063	0.14
46	94.5	2.6	1.4	0.6	0.8	8761.60	94.0%	90.4%	96.4%	14.15	0.1068	0.14
47	94.5	2.7	1.4	0.6	0.8	8941.48	94.2%	89.8%	96.6%	14.21	0.1070	0.14
48	94.6	2.7	1.4	0.5	0.8	9121.67	94.1%	89.9%	96.6%	13.65	0.1029	0.13
49	94.5	2.8	1.4	0.5	0.8	9301.42	94.1%	89.7%	96.5%	13.60	0.1022	0.13
50	94.4	2.8	1.4	0.6	0.8	9481.09	94.1%	89.7%	96.5%	13.56	0.1020	0.13
51	94.6	2.7	1.3	0.6	0.7	9660.17	94.6%	89.8%	96.8%	13.08	0.0992	0.13
52	94.6	2.7	1.4	0.5	0.8	9840.59	94.3%	89.8%	96.6%	12.96	0.0978	0.13
53	94.6	2.8	1.3	0.5	0.7	10020.62	94.4%	89.5%	96.8%	12.43	0.0938	0.12
54	94.3	2.9	1.4	0.6	0.8	10200.39	94.2%	89.3%	96.6%	13.01	0.0975	0.13
55	94.4	2.7	1.5	0.7	0.7	10380.50	93.9%	89.9%	96.7%	13.06	0.0983	0.13


Average Reaction Efficiencies ECM259002-2C & Engelhard Escat 326
Average Reaction Efficiencies
ECM259002-2C & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM259002-2C & Engelhard Escat 326
Average Reformate Composition
ECM259002-2C & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
Mole % H2
100.0
98.0
96.0
94.0
92.0
90.0
0
10
20
30
40
50
60
Cycle
CH4
CO
N2
CO2
H2

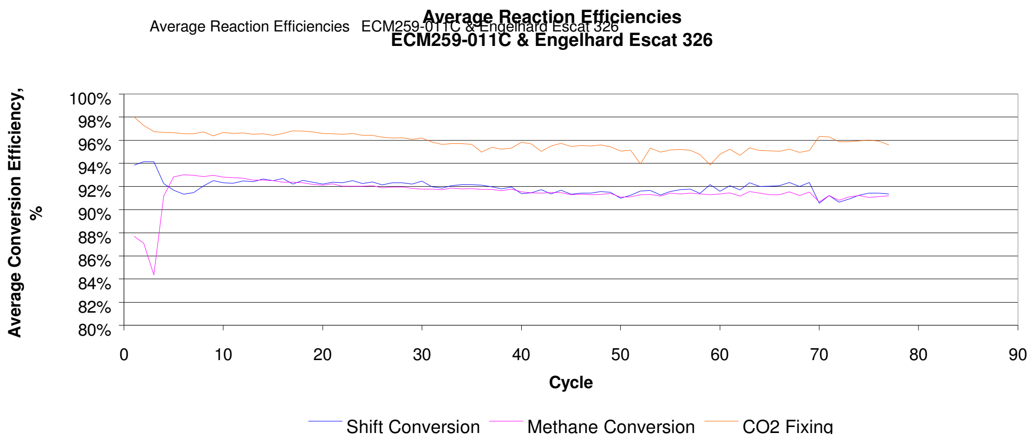

gCO2 Sorbed per g Sorbent ECM259002-2C & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM259002-2C & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
Cycle

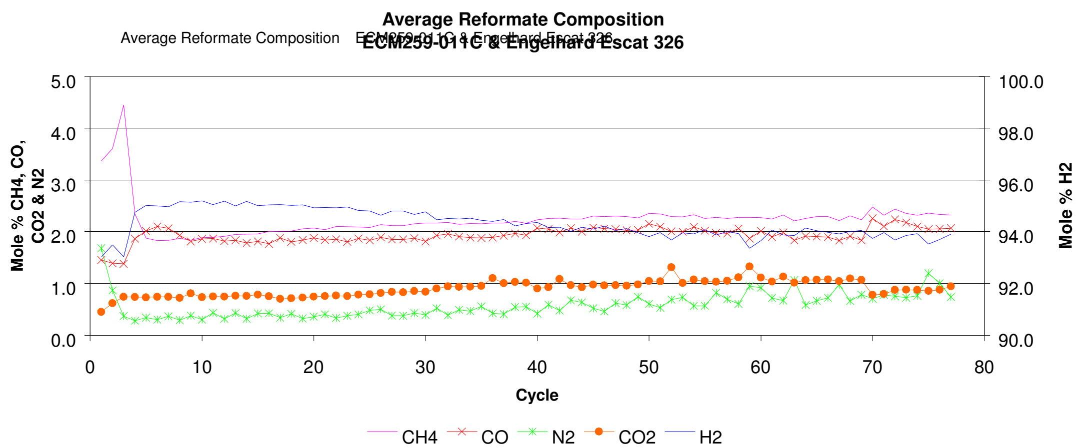
CO_2 Sorption Catalyst	ECM259-011C
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/Al203 (90/10)
Binder	15%Al203
Batch No.	Not Available
Extruded by	CSMP
Oven Atmosphere	N2
Calcined, C	750

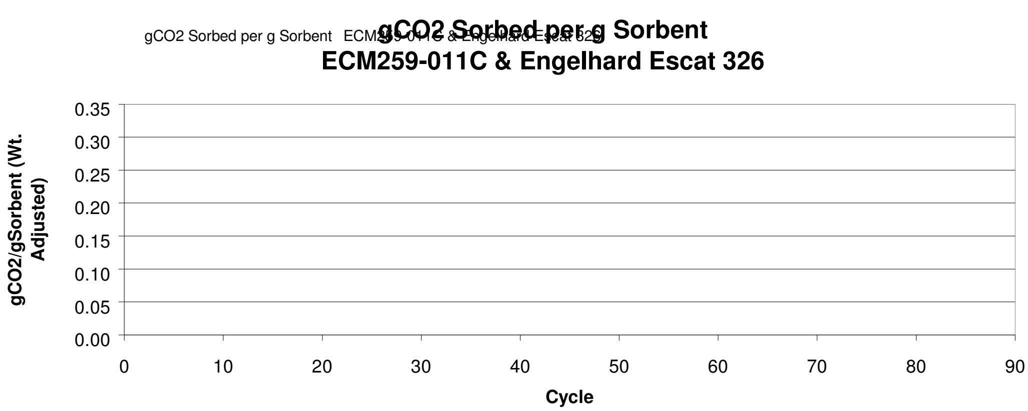
Wt. CO2 extrudate, g	26.13
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	30.63
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	93.0	3.4	1.5	1.7	0.4	365.18	93.8%	87.7%	98.0%	1.87	0.0148	0.02
2	93.5	3.6	1.4	0.9	0.6	547.59	94.2%	87.1%	97.3%	4.95	0.0386	0.05
3	93.0	4.4	1.4	0.4	0.7	752.46	94.2%	84.4%	96.7%	29.21	0.2194	0.26
4	94.7	2.3	1.9	0.3	0.7	932.66	92.3%	91.2%	96.7%	29.95	0.2382	0.28
5	95.0	1.9	2.0	0.3	0.7	1112.74	91.7%	92.8%	96.7%	30.30	0.2439	0.29
6	95.0	1.8	2.1	0.3	0.7	1292.71	91.3%	93.0%	96.6%	30.33	0.2434	0.29
7	95.0	1.8	2.1	0.4	0.7	1472.11	91.5%	93.0%	96.6%	29.68	0.2385	0.29
8	95.2	1.9	1.9	0.3	0.7	1650.83	92.0%	92.8%	96.7%	28.35	0.2292	0.27
9	95.1	1.8	1.8	0.4	0.8	1829.76	92.5%	93.0%	96.4%	27.48	0.2227	0.27
10	95.2	1.9	1.9	0.3	0.7	2010.21	92.3%	92.8%	96.7%	26.74	0.2166	0.26
11	95.0	1.9	1.9	0.4	0.7	2189.47	92.3%	92.8%	96.6%	27.30	0.2209	0.26
12	95.2	1.9	1.8	0.3	0.7	2369.47	92.5%	92.7%	96.6%	26.11	0.2116	0.25
13	95.0	1.9	1.8	0.4	0.8	2548.90	92.4%	92.6%	96.5%	26.70	0.2157	0.26
14	95.2	2.0	1.8	0.3	0.8	2728.82	92.6%	92.6%	96.6%	25.54	0.2069	0.25
15	95.0	2.0	1.8	0.4	0.8	2908.75	92.5%	92.5%	96.4%	26.53	0.2142	0.26
16	95.0	2.0	1.8	0.4	0.8	3088.15	92.7%	92.4%	96.6%	25.54	0.2067	0.25
17	95.0	2.0	1.9	0.3	0.7	3268.83	92.2%	92.4%	96.8%	26.19	0.2113	0.25
18	95.0	2.0	1.8	0.4	0.7	3448.31	92.5%	92.3%	96.8%	25.66	0.2075	0.25
19	95.0	2.1	1.8	0.3	0.7	3628.25	92.4%	92.2%	96.7%	25.45	0.2051	0.25
20	94.9	2.1	1.9	0.4	0.7	3808.34	92.2%	92.1%	96.6%	25.53	0.2050	0.25
21	94.9	2.0	1.8	0.4	0.8	3987.74	92.4%	92.2%	96.6%	24.78	0.1995	0.24
22	94.9	2.1	1.9	0.3	0.8	4167.73	92.3%	92.0%	96.5%	24.58	0.1972	0.24
23	94.9	2.1	1.8	0.4	0.8	4347.14	92.5%	92.0%	96.6%	23.90	0.1923	0.23
24	94.8	2.1	1.9	0.4	0.8	4526.38	92.3%	92.0%	96.4%	23.61	0.1892	0.23
25	94.8	2.1	1.8	0.5	0.8	4705.66	92.4%	92.1%	96.4%	22.97	0.1843	0.22
26	94.6	2.1	1.9	0.5	0.8	4885.64	92.1%	91.9%	96.3%	23.40	0.1867	0.22
27	94.8	2.1	1.9	0.4	0.8	5065.06	92.3%	92.0%	96.2%	21.77	0.1740	0.21
28	94.8	2.1	1.9	0.4	0.8	5244.27	92.3%	92.0%	96.2%	21.11	0.1688	0.20
29	94.7	2.2	1.9	0.4	0.9	5423.93	92.2%	91.8%	96.1%	21.02	0.1674	0.20
30	94.8	2.2	1.8	0.4	0.8	5603.07	92.5%	91.8%	96.2%	20.43	0.1632	0.20
31	94.5	2.2	1.9	0.5	0.9	5782.86	92.0%	91.8%	95.8%	20.41	0.1617	0.19
32	94.5	2.2	2.0	0.4	0.9	5963.05	91.9%	91.7%	95.6%	19.38	0.1528	0.18
33	94.5	2.1	1.9	0.5	0.9	6141.74	92.1%	91.9%	95.7%	19.07	0.1511	0.18
34	94.5	2.2	1.9	0.5	0.9	6321.19	92.2%	91.8%	95.7%	17.88	0.1417	0.17
35	94.4	2.2	1.9	0.6	1.0	6500.33	92.2%	91.8%	95.6%	17.91	0.1419	0.17
36	94.4	2.2	1.9	0.4	1.1	6680.66	92.1%	91.8%	95.0%	17.40	0.1367	0.16
37	94.5	2.2	1.9	0.4	1.0	6859.82	92.0%	91.7%	95.4%	16.71	0.1316	0.16
38	94.2	2.2	2.0	0.5	1.0	7039.56	91.8%	91.6%	95.2%	16.79	0.1316	0.16
39	94.3	2.2	1.9	0.6	1.0	7218.62	92.0%	91.8%	95.3%	16.18	0.1274	0.15
40	94.4	2.2	2.1	0.4	0.9	7399.15	91.4%	91.5%	95.8%	15.57	0.1221	0.15
41	94.2	2.3	2.1	0.6	0.9	7578.45	91.5%	91.5%	95.7%	16.04	0.1257	0.15
42	94.2	2.3	2.0	0.5	1.1	7758.11	91.7%	91.4%	95.0%	14.95	0.1166	0.14
43	94.0	2.2	2.1	0.7	1.0	7937.77	91.4%	91.5%	95.5%	14.87	0.1162	0.14
44	94.2	2.2	2.0	0.6	0.9	8116.85	91.7%	91.5%	95.7%	14.19	0.1115	0.13
45	94.1	2.3	2.1	0.5	1.0	8297.19	91.3%	91.3%	95.5%	13.62	0.1061	0.13
46	94.2	2.3	2.1	0.5	1.0	8476.56	91.4%	91.3%	95.5%	13.20	0.1031	0.12
47	94.0	2.3	2.1	0.6	1.0	8656.06	91.4%	91.3%	95.5%	13.08	0.1021	0.12
48	94.1	2.3	2.0	0.6	1.0	8835.22	91.6%	91.3%	95.6%	12.42	0.0972	0.12
49	94.0	2.3	2.0	0.7	1.0	9015.11	91.5%	91.4%	95.4%	12.42	0.0970	0.12
50	93.8	2.4	2.2	0.6	1.0	9195.41	91.0%	91.1%	95.1%	11.77	0.0908	0.11
51	94.0	2.3	2.1	0.5	1.0	9374.56	91.2%	91.1%	95.2%	11.13	0.0862	0.10
52	93.7	2.3	2.0	0.7	1.3	9554.24	91.6%	91.3%	93.9%	11.22	0.0862	0.10
53	94.0	2.3	2.0	0.7	1.0	9733.25	91.7%	91.3%	95.3%	10.52	0.0821	0.10
54	93.9	2.3	2.1	0.6	1.1	9913.67	91.3%	91.2%	95.0%	9.95	0.0770	0.09
55	94.1	2.3	2.0	0.6	1.0	10092.59	91.6%	91.4%	95.2%	9.26	0.0722	0.09
56	93.9	2.3	2.0	0.8	1.0	10272.22	91.7%	91.4%	95.2%	9.35	0.0730	0.09
57	94.0	2.3	2.0	0.7	1.0	10451.87	91.8%	91.4%	95.1%	9.29	0.0726	0.09
58	93.9	2.3	2.1	0.6	1.1	10632.01	91.4%	91.4%	94.8%	8.57	0.0664	0.08
59	93.4	2.3	1.9	0.9	1.3	10811.67	92.2%	91.3%	93.9%	8.72	0.0674	0.08
60	93.7	2.3	2.0	0.9	1.1	10991.30	91.6%	91.4%	94.8%	8.71	0.0677	0.08
61	94.1	2.2	1.9	0.7	1.0	11171.00	92.1%	91.4%	95.2%	7.48	0.0587	0.07
62	93.9	2.3	2.0	0.7	1.1	11350.95	91.7%	91.2%	94.7%	7.95	0.0617	0.07
63	93.9	2.2	1.8	1.1	1.0	11530.23	92.3%	91.6%	95.3%	7.49	0.0591	0.07
64	94.1	2.3	1.9	0.6	1.1	11710.44	92.0%	91.4%	95.1%	6.79	0.0532	0.06
65	94.0	2.3	1.9	0.7	1.1	11890.29	92.0%	91.3%	95.1%	6.84	0.0535	0.06
66	94.0	2.3	1.9	0.7	1.1	12069.70	92.1%	91.3%	95.0%	6.53	0.0510	0.06
67	93.9	2.2	1.8	1.0	1.0	12249.57	92.4%	91.6%	95.2%	6.78	0.0535	0.06
68	94.0	2.3	1.9	0.7	1.1	12429.98	92.0%	91.2%	95.0%	6.17	0.0482	0.06
69	94.1	2.2	1.8	0.8	1.1	12609.04	92.3%	91.5%	95.1%	5.79	0.0455	0.05
70	93.7	2.5	2.3	0.7	0.8	12790.63	90.6%	90.7%	96.3%	6.79	0.0526	0.06
71	94.0	2.3	2.1	0.8	0.8	12969.66	91.2%	91.2%	96.3%	6.49	0.0509	0.06
72	93.7	2.4	2.2	0.8	0.9	13150.37	90.7%	90.8%	95.9%	6.83	0.0528	0.06
73	93.9	2.4	2.2	0.7	0.9	13329.69	90.9%	91.1%	95.9%	6.57	0.0511	0.06
74	93.9	2.3	2.1	0.8	0.9	13509.75	91.2%	91.2%	95.9%	6.33	0.0494	0.06
75	93.5	2.4	2.0	1.2	0.9	13689.44	91.4%	91.1%	96.0%	6.37	0.0499	0.06
76	93.7	2.3	2.1	1.0	0.9	13869.29	91.4%	91.1%	95.9%	6.34	0.0496	0.06
77	93.9	2.3	2.1	0.7	0.9	14049.44	91.4%	91.2%	95.6%	5.34	0.0416	0.05


Average Reaction Efficiencies ECM259-011C & Engelhard Escat 326
Average Reaction Efficiencies
ECM259-011C & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
70
80
90
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition ECM259-011C & Engelhard Escat 326
Average Reformate Composition
ECM259-011C & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
10
20
30
40
50
60
70
80
Cycle
CH4
CO
N2
CO2
H2

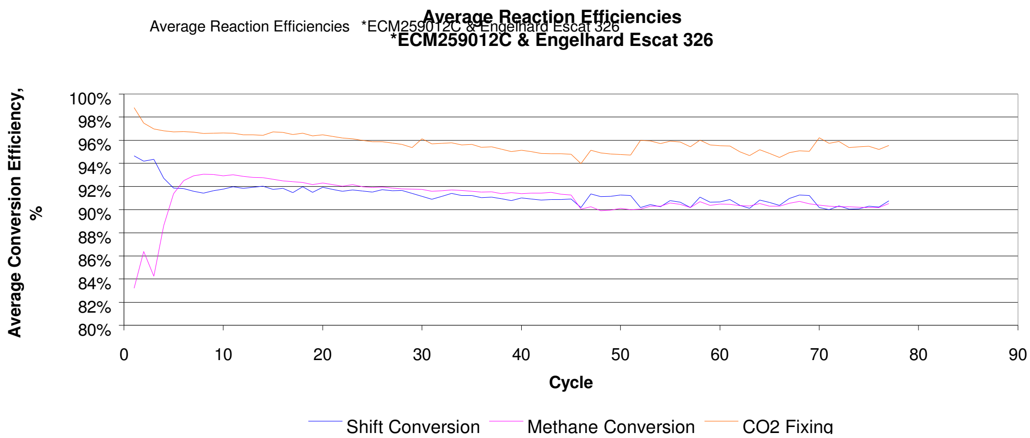

gCO2 Sorbed per g Sorbent ECM259-011C & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
ECM259-011C & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
90
Cycle

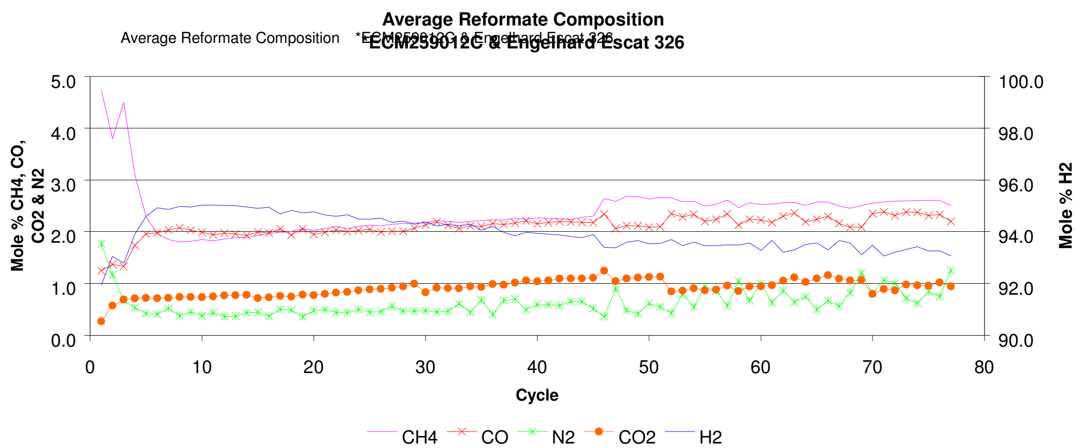
CO_2 Sorption Catalyst	*ECM259012C
Reforming Catalyst: 0.5% rhodium on	Engelhard Escat 326
Composition CO_2 sorb	CaO/Al203 (90/10)
Binder	15%Al203
Batch No.	ECM259007-009
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

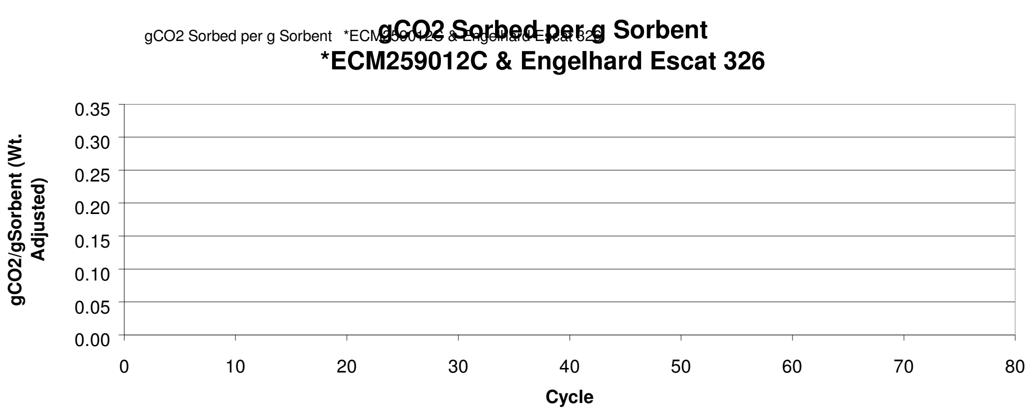
Wt. CO2 extrudate, g	26.57
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	31.07
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	91.9	4.7	1.2	1.8	0.3	376.29	94.7%	83.2%	98.8%	1.22	0.0091	0.01
2	93.1	3.8	1.4	1.2	0.6	560.05	94.2%	86.4%	97.5%	5.58	0.0426	0.05
3	92.8	4.5	1.3	0.7	0.7	754.65	94.3%	84.2%	97.0%	20.37	0.1509	0.19
4	93.9	3.1	1.7	0.5	0.7	941.09	92.7%	88.6%	96.8%	26.86	0.2056	0.26
5	94.6	2.3	2.0	0.4	0.7	1121.07	91.9%	91.4%	96.7%	27.05	0.2113	0.27
6	94.9	2.0	2.0	0.4	0.7	1300.47	91.8%	92.5%	96.8%	26.02	0.2057	0.26
7	94.9	1.8	2.0	0.5	0.7	1480.30	91.6%	92.9%	96.7%	26.04	0.2062	0.26
8	95.0	1.8	2.1	0.4	0.7	1660.41	91.4%	93.1%	96.6%	25.93	0.2051	0.26
9	95.0	1.8	2.0	0.4	0.7	1839.91	91.6%	93.0%	96.6%	25.51	0.2021	0.26
10	95.0	1.8	2.0	0.4	0.7	2019.33	91.8%	92.9%	96.6%	24.84	0.1969	0.25
11	95.0	1.8	1.9	0.4	0.7	2198.81	92.0%	93.0%	96.6%	24.30	0.1932	0.24
12	95.0	1.9	2.0	0.4	0.8	2378.93	91.8%	92.9%	96.5%	24.10	0.1908	0.24
13	95.0	1.9	2.0	0.4	0.8	2558.70	91.9%	92.8%	96.5%	23.63	0.1871	0.24
14	95.0	1.9	1.9	0.4	0.8	2737.85	92.0%	92.8%	96.4%	23.76	0.1882	0.24
15	94.9	1.9	2.0	0.4	0.7	2918.19	91.8%	92.6%	96.7%	23.70	0.1875	0.24
16	94.9	2.0	2.0	0.4	0.7	3097.99	91.8%	92.5%	96.7%	23.26	0.1837	0.23
17	94.7	2.0	2.1	0.5	0.8	3278.03	91.5%	92.4%	96.5%	23.92	0.1878	0.24
18	94.8	2.0	1.9	0.5	0.7	3457.30	92.0%	92.4%	96.6%	22.66	0.1789	0.23
19	94.7	2.1	2.1	0.4	0.8	3637.88	91.5%	92.2%	96.4%	22.74	0.1778	0.23
20	94.8	2.0	1.9	0.5	0.8	3816.74	91.9%	92.3%	96.5%	22.06	0.1737	0.22
21	94.6	2.1	2.0	0.5	0.8	3996.30	91.8%	92.2%	96.3%	22.16	0.1737	0.22
22	94.6	2.1	2.0	0.4	0.8	4176.37	91.6%	92.0%	96.2%	21.51	0.1678	0.21
23	94.7	2.1	2.0	0.4	0.8	4355.37	91.7%	92.2%	96.1%	20.92	0.1636	0.21
24	94.5	2.1	2.0	0.5	0.9	4534.96	91.6%	92.0%	96.0%	20.47	0.1593	0.20
25	94.5	2.1	2.0	0.4	0.9	4714.47	91.5%	91.9%	95.9%	19.96	0.1550	0.20
26	94.5	2.1	2.0	0.5	0.9	4893.65	91.7%	92.0%	95.9%	18.64	0.1451	0.18
27	94.4	2.1	2.0	0.6	0.9	5072.91	91.6%	91.9%	95.8%	18.98	0.1472	0.19
28	94.4	2.2	2.0	0.5	0.9	5252.46	91.7%	91.8%	95.7%	17.76	0.1376	0.17
29	94.3	2.2	2.1	0.5	1.0	5432.42	91.4%	91.8%	95.4%	17.19	0.1324	0.17
30	94.4	2.2	2.1	0.5	0.8	5611.89	91.1%	91.8%	96.1%	17.08	0.1322	0.17
31	94.2	2.2	2.2	0.4	0.9	5791.96	90.9%	91.6%	95.7%	16.57	0.1271	0.16
32	94.3	2.2	2.1	0.5	0.9	5970.71	91.2%	91.6%	95.7%	15.80	0.1216	0.15
33	94.2	2.2	2.1	0.6	0.9	6149.77	91.4%	91.7%	95.8%	15.23	0.1177	0.15
34	94.3	2.2	2.1	0.4	0.9	6329.69	91.2%	91.7%	95.6%	14.66	0.1128	0.14
35	94.1	2.2	2.1	0.7	0.9	6508.93	91.2%	91.6%	95.7%	14.58	0.1122	0.14
36	94.2	2.2	2.2	0.4	1.0	6688.91	91.0%	91.5%	95.4%	13.95	0.1068	0.14
37	94.0	2.2	2.1	0.7	1.0	6868.23	91.1%	91.6%	95.4%	13.90	0.1065	0.14
38	93.8	2.3	2.2	0.7	1.0	7048.01	90.9%	91.4%	95.2%	13.28	0.1012	0.13
39	94.0	2.2	2.2	0.5	1.1	7227.81	90.8%	91.5%	95.0%	12.65	0.0962	0.12
40	93.9	2.3	2.2	0.6	1.0	7407.17	91.0%	91.4%	95.1%	12.12	0.0923	0.12
41	93.9	2.3	2.2	0.6	1.1	7586.59	90.9%	91.4%	95.0%	12.03	0.0915	0.12
42	93.9	2.2	2.2	0.6	1.1	7766.55	90.8%	91.4%	94.8%	11.35	0.0861	0.11
43	93.8	2.2	2.2	0.7	1.1	7945.76	90.9%	91.5%	94.8%	11.40	0.0866	0.11
44	93.8	2.3	2.2	0.7	1.1	8125.53	90.9%	91.3%	94.8%	10.73	0.0814	0.10
45	93.9	2.3	2.2	0.5	1.1	8305.20	90.9%	91.3%	94.8%	10.10	0.0765	0.10
46	93.4	2.6	2.3	0.4	1.2	8666.85	90.2%	90.1%	94.0%	4.89	0.0360	0.05
47	93.4	2.6	2.1	0.9	1.0	8843.69	91.4%	90.2%	95.1%	8.74	0.0660	0.08
48	93.6	2.7	2.1	0.5	1.1	9024.36	91.1%	89.9%	94.9%	7.74	0.0579	0.07
49	93.7	2.7	2.1	0.4	1.1	9203.98	91.2%	89.9%	94.8%	7.68	0.0575	0.07
50	93.5	2.6	2.1	0.6	1.1	9383.57	91.3%	90.1%	94.8%	7.73	0.0580	0.07
51	93.5	2.7	2.1	0.5	1.1	9563.20	91.2%	90.0%	94.7%	7.69	0.0576	0.07
52	93.7	2.7	2.3	0.4	0.8	9744.36	90.2%	90.1%	96.0%	7.71	0.0579	0.07
53	93.5	2.6	2.3	0.8	0.9	9923.89	90.4%	90.3%	95.9%	8.06	0.0608	0.08
54	93.6	2.6	2.3	0.5	0.9	10103.77	90.2%	90.3%	95.7%	7.57	0.0569	0.07
55	93.5	2.5	2.2	0.9	0.9	10283.09	90.8%	90.6%	95.9%	7.62	0.0579	0.07
56	93.5	2.5	2.2	0.9	0.9	10462.86	90.6%	90.5%	95.8%	7.70	0.0583	0.07
57	93.5	2.6	2.3	0.6	1.0	10643.49	90.2%	90.2%	95.4%	7.12	0.0532	0.07
58	93.5	2.5	2.1	1.0	0.9	10821.98	91.1%	90.7%	96.0%	7.00	0.0535	0.07
59	93.6	2.6	2.2	0.7	0.9	11002.49	90.6%	90.4%	95.6%	6.47	0.0488	0.06
60	93.3	2.5	2.2	1.0	0.9	11182.03	90.7%	90.5%	95.5%	7.06	0.0533	0.07
61	93.7	2.5	2.2	0.6	1.0	11361.98	90.9%	90.5%	95.5%	5.76	0.0436	0.06
62	93.2	2.6	2.3	0.9	1.1	11542.22	90.4%	90.3%	95.0%	6.33	0.0472	0.06
63	93.3	2.6	2.4	0.6	1.1	11722.18	90.1%	90.3%	94.7%	6.32	0.0469	0.06
64	93.5	2.5	2.2	0.7	1.0	11901.55	90.8%	90.5%	95.2%	5.76	0.0434	0.05
65	93.6	2.6	2.2	0.5	1.1	12081.66	90.6%	90.3%	94.8%	5.69	0.0425	0.05
66	93.3	2.6	2.3	0.7	1.2	12261.83	90.4%	90.3%	94.5%	5.68	0.0422	0.05
67	93.7	2.5	2.2	0.6	1.1	12441.27	91.0%	90.6%	94.9%	5.04	0.0380	0.05
68	93.6	2.5	2.1	0.8	1.1	12621.01	91.3%	90.7%	95.1%	5.00	0.0379	0.05
69	93.1	2.5	2.1	1.2	1.1	12800.90	91.2%	90.5%	95.0%	5.02	0.0379	0.05
70	93.5	2.6	2.3	0.8	0.8	12981.61	90.2%	90.4%	96.2%	5.66	0.0428	0.05
71	93.1	2.6	2.4	1.1	0.9	13161.53	90.0%	90.3%	95.7%	5.62	0.0422	0.05
72	93.2	2.6	2.3	1.0	0.9	13341.20	90.3%	90.2%	95.9%	5.68	0.0427	0.05
73	93.3	2.6	2.4	0.7	1.0	13521.54	90.1%	90.2%	95.4%	5.09	0.0380	0.05
74	93.4	2.6	2.4	0.6	1.0	13701.33	90.1%	90.2%	95.4%	5.06	0.0377	0.05
75	93.3	2.6	2.3	0.8	1.0	13881.12	90.3%	90.2%	95.5%	5.03	0.0376	0.05
76	93.3	2.6	2.3	0.7	1.0	14061.43	90.2%	90.2%	95.2%	4.39	0.0328	0.04
77	93.1	2.5	2.2	1.3	0.9	14240.55	90.8%	90.5%	95.6%	5.07	0.0383	0.05


Average Reaction Efficiencies *ECM259012C & Engelhard Escat 326
Average Reaction Efficiencies
*ECM259012C & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
70
80
90
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *ECM259012C & Engelhard Escat 326
Average Reformate Composition
*ECM259012C & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
10
20
30
40
50
60
70
80
Cycle
CH4
CO
N2
CO2
H2

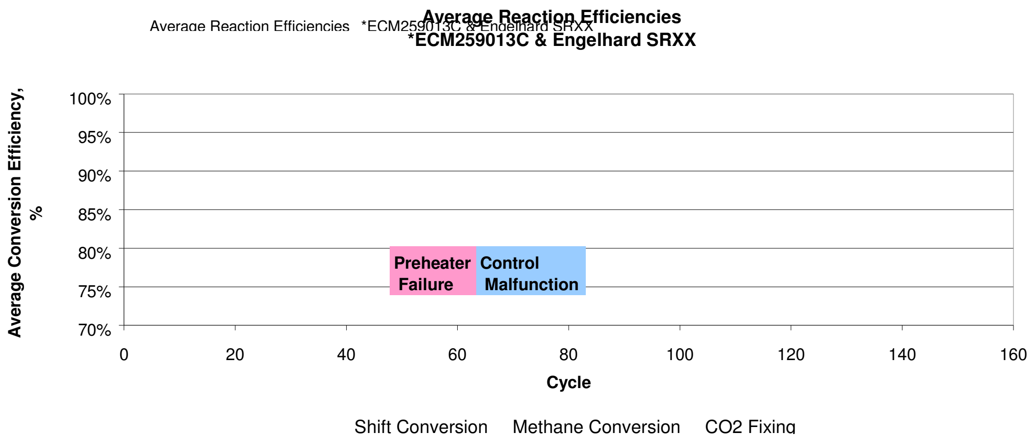

gCO2 Sorbed per g Sorbent *ECM259012C & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*ECM259012C & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
Cycle

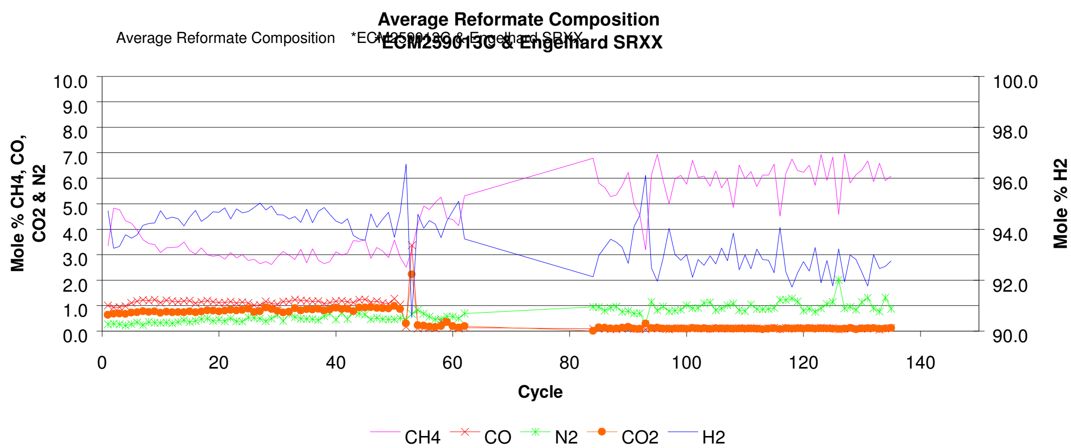
CO_2 Sorption Catalyst	*ECM259013C
Reforming Catalyst: 0.5% rhodium o	Engelhard SRXX
Composition CO_2 sorb	CaO/Al2O3 (90/10)
Binder	15%Al203
Batch No.	HCB326030B
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

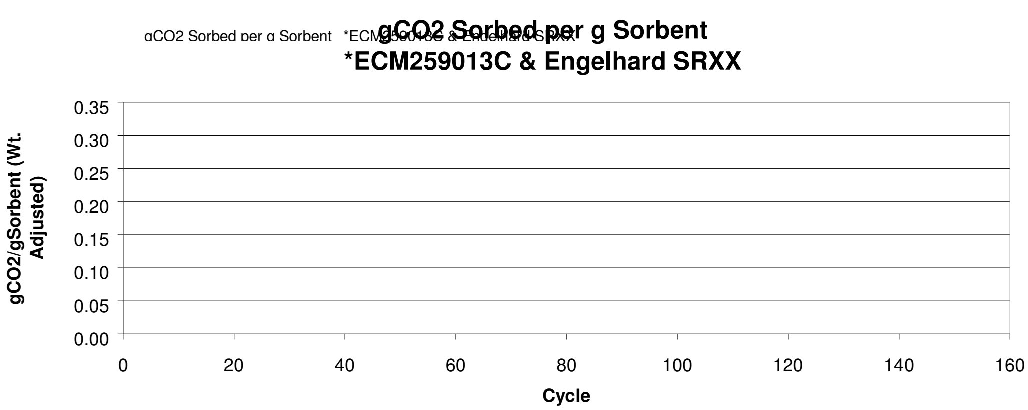
Wt. CO2 extrudate, g	24.75
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	29.25
Total Bed Vol., ml	40.0

Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	94.7	3.3	1.0	0.3	0.6	302.59	95.8%	87.9%	97.3%	29.74	0.0042	0.28
2	93.3	4.8	0.9	0.3	0.7	481.64	96.0%	83.1%	97.1%	29.96	0.0040	0.26
3	93.3	4.8	0.9	0.3	0.7	661.61	96.0%	83.4%	97.1%	29.18	0.0040	0.26
4	93.8	4.3	1.0	0.2	0.7	841.00	95.9%	84.7%	97.1%	28.78	0.0041	0.26
5	93.6	4.2	1.1	0.3	0.7	1021.67	95.3%	85.0%	96.9%	29.20	0.0041	0.26
6	93.8	4.0	1.2	0.3	0.7	1200.74	95.0%	85.9%	96.8%	29.09	0.0041	0.26
7	94.1	3.6	1.2	0.2	0.8	1381.77	94.8%	87.0%	96.6%	27.58	0.0041	0.25
8	94.2	3.4	1.2	0.4	0.7	1559.29	95.0%	87.5%	96.7%	27.28	0.0042	0.25
9	94.2	3.4	1.2	0.3	0.8	1739.75	94.8%	87.6%	96.6%	26.82	0.0041	0.24
10	94.7	3.1	1.1	0.3	0.7	1916.42	95.3%	88.7%	96.9%	23.80	0.0042	0.22
11	94.4	3.3	1.2	0.3	0.8	2097.45	94.9%	88.0%	96.7%	25.15	0.0042	0.23
12	94.5	3.3	1.2	0.3	0.7	2277.14	95.1%	88.0%	96.8%	24.08	0.0042	0.22
13	94.4	3.3	1.2	0.4	0.7	2459.00	95.2%	87.9%	96.8%	26.05	0.0042	0.24
14	94.1	3.5	1.2	0.4	0.7	2636.08	95.0%	87.3%	96.8%	23.24	0.0041	0.21
15	94.5	3.2	1.2	0.4	0.8	2815.81	95.0%	88.4%	96.6%	22.99	0.0042	0.21
16	94.7	3.0	1.1	0.4	0.7	2994.90	95.4%	88.9%	96.8%	22.24	0.0042	0.21
17	94.3	3.3	1.2	0.5	0.8	3174.64	95.2%	88.1%	96.7%	22.59	0.0042	0.21
18	94.5	3.0	1.2	0.5	0.8	3354.97	95.0%	89.0%	96.4%	22.54	0.0042	0.21
19	94.7	2.9	1.2	0.4	0.8	3534.13	95.2%	89.2%	96.5%	21.50	0.0042	0.20
20	94.7	3.0	1.1	0.5	0.8	3713.80	95.3%	89.0%	96.6%	21.17	0.0042	0.20
21	94.8	2.8	1.1	0.4	0.8	3892.88	95.3%	89.6%	96.5%	20.68	0.0043	0.19
22	94.4	3.1	1.2	0.5	0.8	4073.39	95.2%	88.7%	96.3%	21.06	0.0042	0.19
23	94.8	2.9	1.1	0.4	0.8	4253.04	95.4%	89.4%	96.5%	20.47	0.0042	0.19
24	94.6	3.0	1.1	0.4	0.8	4432.91	95.2%	89.0%	96.4%	20.04	0.0042	0.19
25	94.7	2.8	1.1	0.5	0.9	4611.51	95.4%	89.7%	96.1%	19.73	0.0043	0.18
26	94.9	2.8	1.0	0.5	0.7	4790.43	95.8%	89.6%	96.8%	18.15	0.0043	0.17
27	95.0	2.6	1.0	0.5	0.8	4970.09	95.7%	90.2%	96.6%	17.89	0.0043	0.17
28	94.8	2.7	1.2	0.4	0.9	5151.54	95.1%	89.9%	95.9%	18.75	0.0042	0.17
29	94.9	2.6	1.1	0.5	0.9	5330.36	95.5%	90.2%	96.2%	18.36	0.0043	0.17
30	94.6	2.9	1.1	0.6	0.8	5508.69	95.6%	89.3%	96.6%	16.67	0.0043	0.16
31	94.6	3.1	1.2	0.4	0.7	5690.00	95.2%	88.5%	96.8%	17.23	0.0042	0.16
32	94.4	3.0	1.2	0.7	0.8	5869.33	95.1%	89.0%	96.7%	17.06	0.0042	0.16
33	94.5	2.8	1.2	0.5	0.9	6050.75	94.8%	89.6%	96.0%	18.18	0.0042	0.17
34	94.3	3.2	1.2	0.5	0.8	6228.98	95.0%	88.3%	96.4%	16.20	0.0042	0.15
35	94.8	2.7	1.2	0.5	0.9	6408.85	95.0%	90.1%	96.2%	15.84	0.0043	0.15
36	94.3	3.2	1.2	0.5	0.8	6588.56	95.1%	88.2%	96.3%	15.68	0.0042	0.14
37	94.7	2.8	1.2	0.4	0.9	6768.31	95.1%	89.6%	96.2%	14.90	0.0042	0.14
38	94.9	2.7	1.1	0.6	0.8	6946.68	95.5%	90.1%	96.5%	14.42	0.0043	0.14
39	94.6	2.7	1.1	0.7	0.8	7127.57	95.3%	89.8%	96.3%	15.18	0.0043	0.14
40	94.3	3.1	1.2	0.4	0.9	7309.20	95.1%	88.5%	96.0%	15.95	0.0042	0.15
41	94.2	3.0	1.2	0.7	0.9	7487.00	95.0%	89.0%	96.2%	13.97	0.0042	0.13
42	94.4	3.1	1.1	0.5	0.9	7666.93	95.2%	88.8%	96.1%	13.53	0.0042	0.12
43	93.7	3.6	1.1	0.8	0.8	7845.76	95.2%	87.1%	96.6%	12.68	0.0041	0.12
44	93.6	3.5	1.2	0.7	0.9	8026.27	94.8%	87.2%	95.9%	13.63	0.0041	0.12
45	93.6	3.6	1.2	0.6	0.9	8206.74	94.7%	87.0%	95.9%	13.51	0.0041	0.12
46	94.6	2.8	1.1	0.5	0.9	8386.67	95.2%	89.4%	95.9%	13.33	0.0042	0.12
47	94.1	3.3	1.2	0.5	0.9	8566.68	95.0%	88.0%	96.0%	12.66	0.0041	0.12
48	94.4	3.1	1.1	0.5	0.9	8746.26	95.4%	88.5%	96.1%	12.17	0.0042	0.11
49	94.7	2.9	1.1	0.5	0.9	8925.89	95.5%	89.4%	96.1%	11.92	0.0042	0.11
50	93.7	3.6	1.3	0.5	1.0	9106.87	94.6%	87.0%	95.6%	12.25	0.0041	0.11
51	94.7	2.9	1.0	0.5	0.9	9284.61	95.6%	89.3%	96.2%	10.50	0.0042	0.10
52	96.6	2.5	0.2	0.5	0.3	9466.20	99.3%	90.8%	98.7%	13.16	0.0046	0.13
53	90.5	3.2	3.4	0.7	2.2	9816.01	85.6%	88.1%	88.8%	0.83	0.0035	0.01
54	94.6	4.2	0.1	0.8	0.2	10006.93	99.6%	85.1%	99.1%	14.07	0.0043	0.13
55	94.0	4.9	0.1	0.7	0.2	10188.83	99.5%	83.1%	99.1%	15.62	0.0042	0.14
56	94.3	4.8	0.1	0.6	0.2	10366.73	99.5%	83.4%	99.3%	12.45	0.0042	0.12
57	94.2	5.0	0.1	0.5	0.2	10546.94	99.5%	82.7%	99.3%	12.30	0.0042	0.11
58	93.7	5.3	0.4	0.5	0.2	10727.44	98.4%	82.0%	99.2%	13.00	0.0041	0.12
59	94.3	4.4	0.3	0.6	0.3	10905.53	98.8%	84.4%	98.4%	11.49	0.0042	0.11
60	94.7	4.4	0.1	0.6	0.2	11085.05	99.5%	84.6%	99.2%	11.66	0.0043	0.11
61	95.1	4.1	0.1	0.5	0.1	11265.11	99.6%	85.3%	99.4%	10.61	0.0044	0.10
62	93.6	5.3	0.1	0.7	0.2	11446.47	99.4%	81.8%	99.2%	12.04	0.0042	0.11
84	92.1	6.8	0.1	0.9	0.0	15898.33	99.6%	77.5%	100.0%	11.46	0.0040	0.10
85	93.0	5.8	0.1	0.9	0.1	16076.80	99.6%	80.1%	99.4%	9.43	0.0041	0.08
86	93.3	5.6	0.1	0.8	0.1	16255.55	99.6%	80.7%	99.5%	8.30	0.0041	0.08
87	93.6	5.3	0.1	0.9	0.1	16434.90	99.7%	81.7%	99.6%	7.63	0.0042	0.07
88	93.5	5.3	0.1	1.0	0.1	16614.97	99.7%	81.6%	99.6%	8.27	0.0042	0.08
89	93.3	5.7	0.1	0.8	0.1	16795.51	99.6%	80.6%	99.5%	7.97	0.0041	0.07
90	92.7	6.2	0.1	0.8	0.2	16975.58	99.5%	78.9%	99.3%	7.08	0.0040	0.06
91	94.1	5.0	0.1	0.7	0.1	17154.51	99.6%	82.7%	99.6%	6.52	0.0042	0.06
92	94.5	4.6	0.1	0.7	0.1	17336.73	99.7%	84.1%	99.7%	9.05	0.0043	0.09
93	96.1	3.2	0.1	0.3	0.3	17529.39	99.7%	88.8%	98.8%	2.50	0.0045	0.02
94	92.5	6.1	0.1	1.1	0.1	18234.83	99.6%	79.3%	99.5%	6.81	0.0041	0.06
95	92.0	6.9	0.1	0.8	0.1	18415.72	99.5%	77.0%	99.5%	7.19	0.0039	0.06
96	92.9	5.9	0.1	1.0	0.1	18595.41	99.5%	79.8%	99.6%	6.94	0.0041	0.06
97	94.0	5.0	0.1	0.8	0.1	18774.11	99.7%	82.6%	99.6%	5.69	0.0042	0.05
98	93.0	6.0	0.1	0.8	0.1	18956.32	99.6%	79.7%	99.6%	7.53	0.0041	0.07
99	92.8	6.1	0.1	0.8	0.1	19133.60	99.5%	79.3%	99.6%	4.82	0.0041	0.04
100	93.0	5.8	0.1	1.0	0.1	19314.05	99.6%	80.2%	99.7%	5.82	0.0041	0.05
101	92.1	6.7	0.1	0.9	0.1	19496.03	99.5%	77.7%	99.5%	6.95	0.0040	0.06
102	92.8	6.0	0.1	0.9	0.1	19674.09	99.6%	79.5%	99.6%	5.60	0.0041	0.05
103	92.6	6.1	0.1	1.1	0.1	19854.47	99.6%	79.5%	99.5%	6.22	0.0041	0.06
104	93.0	5.7	0.1	1.1	0.1	20034.13	99.6%	80.5%	99.6%	6.25	0.0041	0.06
105	92.6	6.3	0.1	0.8	0.1	20215.86	99.6%	78.8%	99.6%	6.77	0.0040	0.06
106	93.3	5.6	0.1	0.9	0.1	20395.10	99.6%	80.8%	99.6%	7.24	0.0041	0.07
107	92.8	6.0	0.1	1.0	0.1	20574.26	99.5%	79.7%	99.6%	5.72	0.0041	0.05
108	93.8	4.9	0.1	1.1	0.1	20753.69	99.6%	83.0%	99.6%	4.99	0.0043	0.05
109	92.4	6.5	0.1	0.8	0.1	20935.77	99.5%	78.2%	99.6%	7.02	0.0040	0.06
110	93.0	6.0	0.1	0.8	0.1	21114.60	99.5%	79.7%	99.6%	4.33	0.0041	0.04
111	92.4	6.3	0.1	1.0	0.1	21295.02	99.5%	78.9%	99.6%	7.05	0.0040	0.06
112	93.2	5.7	0.1	0.9	0.1	21475.51	99.6%	80.6%	99.6%	6.22	0.0041	0.06
113	92.8	6.1	0.1	0.9	0.1	21653.98	99.6%	79.2%	99.7%	5.12	0.0041	0.05
114	92.8	6.1	0.1	0.9	0.1	21834.29	99.5%	79.3%	99.6%	4.97	0.0041	0.04
115	92.3	6.5	0.1	0.9	0.1	22014.77	99.4%	78.0%	99.6%	6.35	0.0040	0.06
116	94.1	4.5	0.1	1.2	0.1	22193.01	99.7%	84.1%	99.7%	5.03	0.0043	0.05
117	92.3	6.2	0.1	1.2	0.1	22374.30	99.5%	79.0%	99.6%	5.67	0.0040	0.05
118	91.7	6.8	0.1	1.3	0.1	22554.02	99.6%	77.4%	99.6%	5.96	0.0040	0.05
119	92.3	6.3	0.1	1.2	0.1	22733.75	99.5%	78.7%	99.6%	5.15	0.0040	0.05
120	92.7	6.2	0.1	0.8	0.1	22914.09	99.5%	79.1%	99.6%	5.25	0.0040	0.05
121	92.3	6.5	0.1	0.9	0.1	23094.61	99.5%	78.2%	99.6%	5.38	0.0040	0.05
122	93.3	5.7	0.1	0.8	0.1	23274.23	99.5%	80.6%	99.6%	5.76	0.0041	0.05
123	91.9	6.9	0.1	0.9	0.1	23453.77	99.4%	77.0%	99.6%	4.43	0.0039	0.04
124	92.8	5.9	0.1	1.1	0.1	23634.15	99.5%	80.0%	99.6%	5.02	0.0041	0.05
125	91.8	6.8	0.1	1.1	0.1	23813.04	99.5%	77.1%	99.6%	4.45	0.0039	0.04
126	93.2	4.6	0.1	2.0	0.1	23991.11	99.7%	83.8%	99.7%	3.10	0.0043	0.03
127	91.9	7.0	0.1	0.9	0.1	24173.81	99.6%	76.9%	99.6%	5.08	0.0039	0.04
128	93.0	5.8	0.1	0.9	0.1	24354.60	99.6%	80.1%	99.5%	5.60	0.0041	0.05
129	92.8	6.1	0.1	0.8	0.1	24532.50	99.6%	79.3%	99.7%	3.79	0.0041	0.03
130	92.3	6.3	0.1	1.1	0.1	24712.85	99.6%	78.6%	99.6%	3.97	0.0040	0.04
131	91.8	6.7	0.1	1.3	0.1	24893.73	99.6%	77.6%	99.6%	4.91	0.0040	0.04
132	93.0	5.9	0.1	0.9	0.1	25073.61	99.5%	80.0%	99.5%	4.52	0.0041	0.04
133	92.5	6.6	0.1	0.8	0.1	25253.08	99.7%	77.9%	99.6%	2.52	0.0040	0.02
134	92.5	5.9	0.1	1.3	0.1	25433.06	99.6%	79.8%	99.6%	5.03	0.0041	0.05
135	92.8	6.1	0.1	0.9	0.1	25613.90	99.5%	79.5%	99.5%	4.49	0.0041	0.04


Average Reaction Efficiencies   *ECM259013C & Engelhard SRXX
Average Reaction Efficiencies
*ECM259013C & Engelhard SRXX
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
Preheater Failure
Control Malfunction
0
20
40
60
80
100
120
140
160
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition   *ECM259013C & Engelhard SRXX
Average Reformate Composition
*ECM259013C & Engelhard SRXX
Mole % CH4, CO, CO2 & N2
Mole % H2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
20
40
60
80
100
120
140
Cycle
CH4
CO
N2
CO2
H2

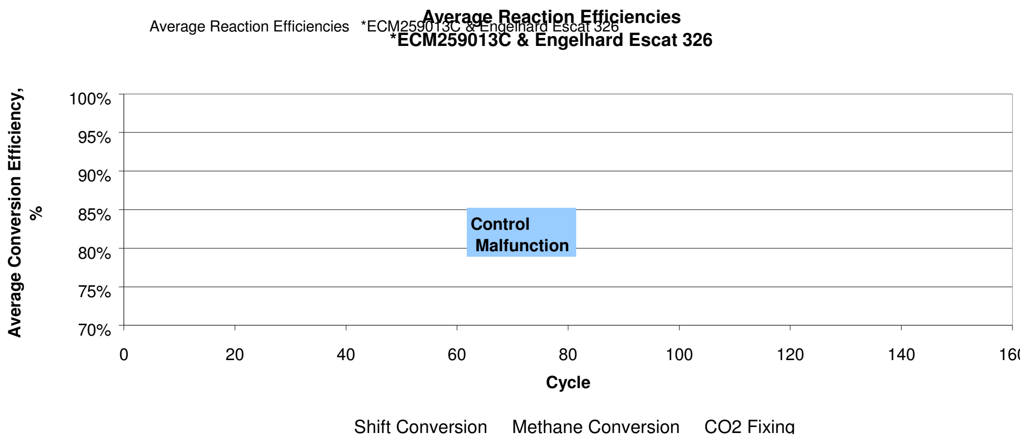

gCO2 Sorbed per g Sorbent   *ECM259013C & Engelhard SRXX
gCO2 Sorbed per g Sorbent
*ECM259013C & Engelhard SRXX
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
120
140
160
Cycle

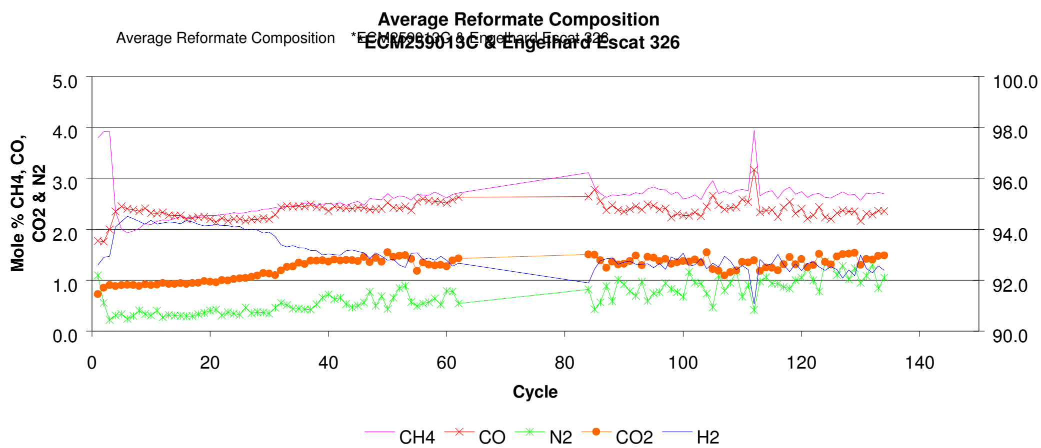
CO_2 Sorption Catalyst	*ECM259013C
Reforming Catalyst: 0.5% rhodium o	Engelhard Escat 326
Composition CO_2 sorb	CaO/Al2O3 (90/10)
Binder	15%Al203
Batch No.	HCB326030B
Extruded by	CSMP
Oven Atmosphere	Air
Calcined, C	750

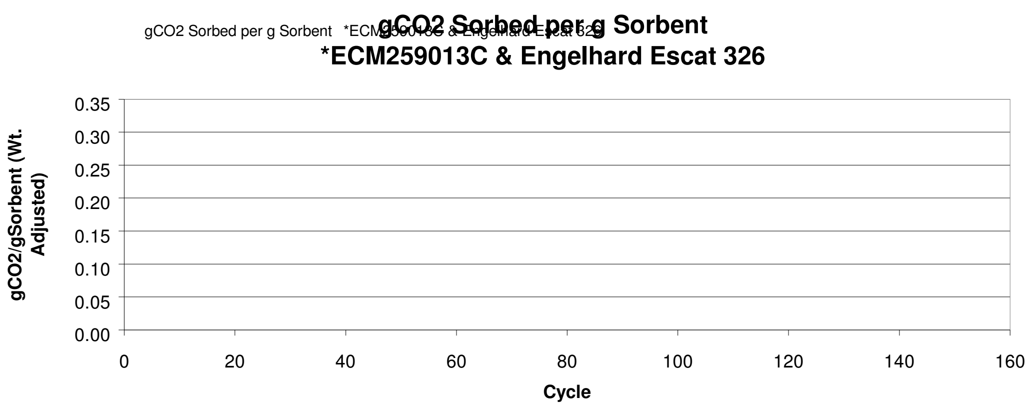
Wt. CO2 extrudate, g	24.72
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.8
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	29.22
Total Bed Vol., ml	40.0

Reactor	R2
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	92.6	3.8	1.8	1.1	0.7	275.43	92.5%	86.4%	96.7%	2.56	0.0040	0.02
2	92.9	3.9	1.8	0.6	0.8	459.24	92.6%	86.1%	96.2%	6.33	0.0040	0.05
3	92.9	3.9	2.0	0.2	0.9	656.23	91.6%	86.0%	95.9%	23.80	0.0039	0.19
4	94.1	2.4	2.3	0.3	0.9	837.99	90.2%	91.1%	95.9%	25.77	0.0041	0.21
5	94.3	2.0	2.4	0.3	0.9	1018.33	89.9%	92.4%	95.8%	25.85	0.0041	0.21
6	94.5	1.9	2.4	0.2	0.9	1197.97	90.1%	92.6%	95.8%	25.11	0.0041	0.21
7	94.4	2.0	2.4	0.3	0.9	1378.01	90.1%	92.5%	95.8%	25.03	0.0041	0.21
8	94.3	2.0	2.4	0.4	0.9	1557.11	90.3%	92.3%	95.9%	25.10	0.0041	0.21
9	94.2	2.1	2.4	0.3	0.9	1737.96	90.0%	92.0%	95.7%	25.03	0.0041	0.21
10	94.3	2.1	2.3	0.3	0.9	1917.10	90.4%	92.0%	95.8%	24.46	0.0041	0.20
11	94.2	2.2	2.3	0.4	0.9	2097.09	90.4%	91.8%	95.7%	24.78	0.0041	0.20
12	94.2	2.2	2.3	0.3	0.9	2277.32	90.3%	91.7%	95.6%	24.27	0.0041	0.20
13	94.3	2.2	2.3	0.3	0.9	2456.97	90.6%	91.7%	95.7%	24.01	0.0041	0.20
14	94.3	2.2	2.3	0.3	0.9	2636.64	90.6%	91.6%	95.7%	23.80	0.0041	0.20
15	94.2	2.2	2.3	0.3	0.9	2816.69	90.6%	91.5%	95.6%	23.86	0.0041	0.20
16	94.3	2.2	2.2	0.3	0.9	2996.17	90.9%	91.6%	95.7%	23.40	0.0041	0.19
17	94.3	2.2	2.2	0.3	0.9	3176.25	90.8%	91.5%	95.6%	22.87	0.0041	0.19
18	94.2	2.3	2.2	0.3	0.9	3356.23	90.7%	91.4%	95.6%	22.58	0.0041	0.19
19	94.1	2.3	2.2	0.4	1.0	3535.80	90.7%	91.4%	95.4%	23.16	0.0041	0.19
20	94.1	2.3	2.2	0.4	1.0	3715.40	90.9%	91.4%	95.5%	22.77	0.0041	0.19
21	94.2	2.3	2.1	0.4	1.0	3894.58	91.1%	91.4%	95.6%	22.37	0.0041	0.18
22	94.2	2.3	2.2	0.3	1.0	4075.58	90.8%	91.3%	95.3%	21.92	0.0041	0.18
23	94.1	2.3	2.2	0.4	1.0	4254.49	91.0%	91.3%	95.4%	21.91	0.0041	0.18
24	94.1	2.3	2.2	0.3	1.0	4434.79	90.8%	91.2%	95.2%	21.91	0.0041	0.18
25	94.1	2.3	2.2	0.3	1.0	4614.33	90.9%	91.3%	95.2%	21.34	0.0041	0.17
26	94.0	2.3	2.2	0.5	1.0	4793.56	91.0%	91.2%	95.1%	21.27	0.0041	0.17
27	94.0	2.4	2.2	0.4	1.1	4973.74	90.9%	91.1%	95.0%	20.20	0.0041	0.16
28	94.0	2.4	2.2	0.4	1.1	5152.80	90.9%	91.1%	94.9%	20.00	0.0041	0.16
29	93.9	2.4	2.2	0.4	1.1	5333.03	90.7%	90.9%	94.7%	19.81	0.0040	0.16
30	93.9	2.4	2.2	0.3	1.1	5512.08	90.8%	90.9%	94.7%	18.83	0.0040	0.15
31	93.7	2.4	2.3	0.5	1.1	5691.91	90.5%	90.8%	94.9%	19.15	0.0040	0.15
32	93.4	2.4	2.4	0.6	1.2	5869.78	89.8%	90.9%	94.3%	17.51	0.0040	0.14
33	93.3	2.4	2.5	0.5	1.3	6049.64	89.7%	90.7%	94.0%	17.06	0.0040	0.14
34	93.4	2.5	2.4	0.4	1.3	6228.37	89.8%	90.7%	94.0%	15.57	0.0040	0.12
35	93.3	2.5	2.5	0.4	1.3	6408.06	89.7%	90.7%	93.6%	15.04	0.0039	0.12
36	93.3	2.5	2.4	0.4	1.3	6586.70	89.8%	90.5%	93.7%	13.81	0.0039	0.11
37	93.2	2.5	2.5	0.4	1.4	6766.55	89.6%	90.5%	93.4%	13.12	0.0039	0.10
38	93.2	2.5	2.4	0.5	1.4	6945.44	89.8%	90.6%	93.4%	11.96	0.0039	0.09
39	93.0	2.5	2.4	0.7	1.4	7124.35	89.8%	90.6%	93.4%	11.95	0.0039	0.09
40	93.0	2.5	2.4	0.7	1.4	7303.87	90.1%	90.5%	93.5%	10.61	0.0039	0.08
41	93.0	2.5	2.4	0.6	1.4	7483.66	89.7%	90.5%	93.3%	10.62	0.0039	0.08
42	93.0	2.5	2.4	0.7	1.4	7663.01	89.8%	90.5%	93.4%	9.60	0.0039	0.08
43	93.2	2.5	2.4	0.5	1.4	7842.52	89.9%	90.6%	93.4%	9.43	0.0039	0.07
44	93.2	2.5	2.4	0.5	1.4	8022.25	89.9%	90.5%	93.4%	8.27	0.0039	0.07
45	93.1	2.5	2.4	0.5	1.4	8201.47	89.8%	90.4%	93.5%	8.12	0.0039	0.06
46	93.1	2.5	2.4	0.6	1.5	8381.62	89.8%	90.6%	93.1%	8.27	0.0039	0.06
47	92.9	2.6	2.4	0.8	1.4	8561.14	90.0%	90.1%	93.6%	7.11	0.0039	0.06
48	93.1	2.6	2.4	0.5	1.4	8741.39	90.0%	90.2%	93.2%	7.30	0.0039	0.06
49	92.9	2.6	2.4	0.7	1.4	8920.33	89.9%	90.2%	93.6%	6.36	0.0039	0.05
50	92.8	2.7	2.5	0.4	1.5	9101.17	89.4%	89.8%	92.6%	6.53	0.0038	0.05
51	92.8	2.6	2.4	0.7	1.5	9280.42	89.8%	90.1%	93.1%	6.32	0.0039	0.05
52	92.6	2.7	2.4	0.8	1.5	9459.66	89.9%	90.0%	93.0%	6.60	0.0039	0.05
53	92.5	2.6	2.4	0.9	1.5	9639.79	89.7%	90.0%	92.9%	6.34	0.0039	0.05
54	93.0	2.6	2.4	0.6	1.4	9819.25	90.1%	90.3%	93.3%	5.65	0.0039	0.04
55	93.1	2.7	2.5	0.5	1.2	10000.10	89.3%	89.9%	94.4%	5.69	0.0039	0.04
56	92.8	2.7	2.6	0.5	1.3	10180.63	89.1%	89.9%	93.5%	5.80	0.0039	0.04
57	92.9	2.7	2.6	0.6	1.3	10359.93	89.2%	90.0%	93.8%	5.65	0.0039	0.04
58	92.8	2.7	2.5	0.6	1.3	10539.58	89.3%	89.7%	93.9%	4.93	0.0039	0.04
59	92.9	2.7	2.5	0.5	1.3	10719.34	89.4%	89.9%	93.8%	4.90	0.0039	0.04
60	92.8	2.6	2.5	0.8	1.3	10899.03	89.4%	90.1%	94.0%	4.97	0.0039	0.04
61	92.6	2.7	2.6	0.8	1.4	11079.18	89.2%	89.9%	93.3%	5.77	0.0039	0.04
62	92.7	2.7	2.6	0.5	1.4	11259.44	88.9%	89.8%	93.1%	4.93	0.0038	0.04
84	91.9	3.1	2.6	0.8	1.5	11441.67	88.8%	88.4%	92.7%	7.22	0.0038	0.05
85	92.4	2.8	2.8	0.4	1.5	15897.72	88.3%	89.4%	92.8%	9.50	0.0038	0.07
86	92.8	2.7	2.6	0.6	1.4	16074.94	89.3%	89.8%	93.3%	6.23	0.0039	0.05
87	92.8	2.6	2.4	0.9	1.2	16252.98	90.0%	90.1%	94.1%	5.72	0.0039	0.05
88	92.9	2.7	2.5	0.6	1.4	16433.65	89.6%	89.9%	93.5%	5.13	0.0039	0.04
89	92.6	2.7	2.4	1.0	1.3	16613.11	90.0%	89.9%	93.8%	5.17	0.0039	0.04
90	92.7	2.7	2.3	0.9	1.3	16792.68	90.1%	89.9%	93.8%	5.14	0.0039	0.04
91	92.7	2.7	2.4	0.8	1.4	16972.96	89.9%	89.9%	93.5%	4.46	0.0039	0.03
92	92.6	2.7	2.5	0.7	1.5	17153.13	89.7%	89.7%	92.9%	5.13	0.0039	0.04
93	92.6	2.7	2.4	1.0	1.3	17332.89	90.0%	89.8%	93.9%	5.20	0.0039	0.04
94	92.6	2.8	2.5	0.6	1.5	17513.85	89.5%	89.5%	93.0%	4.98	0.0039	0.04
95	92.5	2.8	2.5	0.7	1.4	18233.58	89.6%	89.4%	93.1%	4.35	0.0039	0.03
96	92.7	2.8	2.4	0.8	1.4	18412.90	89.9%	89.5%	93.5%	4.36	0.0039	0.03
97	92.4	2.8	2.4	0.9	1.4	18592.92	89.8%	89.5%	93.3%	4.35	0.0039	0.03
98	92.9	2.7	2.2	0.8	1.3	18772.48	90.6%	89.9%	93.8%	4.05	0.0040	0.03
99	92.8	2.7	2.3	0.8	1.4	18952.76	90.3%	89.7%	93.6%	3.95	0.0039	0.03
100	93.1	2.6	2.3	0.7	1.4	19132.66	90.5%	90.2%	93.6%	3.87	0.0039	0.03
101	92.6	2.6	2.3	1.2	1.4	19312.55	90.4%	90.1%	93.6%	4.32	0.0039	0.03
102	92.6	2.7	2.3	1.0	1.4	19492.86	90.2%	89.9%	93.3%	3.77	0.0039	0.03
103	92.9	2.6	2.3	0.9	1.3	19672.29	90.5%	90.2%	93.7%	3.79	0.0040	0.03
104	92.5	2.8	2.4	0.7	1.5	19853.35	89.7%	89.5%	92.6%	3.85	0.0038	0.03
105	92.7	3.0	2.7	0.5	1.2	20393.53	88.8%	89.0%	94.1%	3.98	0.0038	0.03
106	92.5	2.7	2.5	1.1	1.2	20573.00	89.6%	89.8%	94.3%	4.45	0.0039	0.03
107	92.9	2.7	2.4	0.8	1.1	20752.45	90.0%	89.7%	94.8%	3.74	0.0040	0.03
108	92.7	2.7	2.4	0.9	1.2	20932.60	89.8%	89.8%	94.5%	3.85	0.0039	0.03
109	92.4	2.8	2.4	1.2	1.2	21112.72	89.7%	89.6%	94.3%	3.78	0.0039	0.03
110	92.6	2.8	2.6	0.7	1.4	21293.13	89.1%	89.5%	93.5%	3.82	0.0039	0.03
111	92.4	2.8	2.5	0.9	1.3	21473.01	89.3%	89.6%	93.5%	3.72	0.0039	0.03
112	91.1	3.9	3.2	0.4	1.4	21662.25	86.5%	85.7%	93.2%	1.93	0.0036	0.01
113	92.8	2.7	2.3	1.0	1.2	21832.42	90.2%	90.0%	94.5%	3.09	0.0040	0.02
114	92.6	2.7	2.4	1.1	1.2	22012.25	90.0%	89.7%	94.1%	3.83	0.0039	0.03
115	92.7	2.8	2.4	0.9	1.2	22192.40	90.0%	89.6%	94.1%	3.18	0.0039	0.02
116	93.0	2.6	2.2	0.9	1.2	22371.80	90.6%	90.2%	94.4%	3.16	0.0040	0.03
117	92.6	2.8	2.4	0.9	1.3	22552.40	89.8%	89.6%	93.8%	3.12	0.0039	0.02
118	92.3	2.8	2.5	0.8	1.5	22732.98	89.3%	89.4%	93.0%	3.15	0.0038	0.02
119	92.6	2.7	2.3	1.0	1.3	22912.05	90.3%	89.8%	93.8%	3.21	0.0039	0.03
120	92.4	2.7	2.4	1.0	1.4	23092.44	89.9%	89.6%	93.3%	3.20	0.0039	0.02
121	92.7	2.6	2.2	1.2	1.3	23271.64	90.7%	90.0%	94.1%	3.16	0.0040	0.03
122	92.7	2.7	2.3	1.0	1.3	23451.87	90.4%	89.8%	93.9%	2.53	0.0039	0.02
123	92.5	2.7	2.4	0.8	1.5	23632.30	89.7%	89.8%	92.8%	3.16	0.0039	0.02
124	92.4	2.6	2.2	1.4	1.4	23811.77	90.6%	90.0%	93.6%	3.18	0.0039	0.03
125	92.5	2.6	2.2	1.3	1.3	23991.76	90.7%	90.1%	93.9%	2.52	0.0040	0.02
126	92.4	2.7	2.3	1.1	1.5	24171.91	90.2%	89.9%	93.1%	3.17	0.0039	0.02
127	92.1	2.7	2.4	1.3	1.5	24352.13	90.0%	89.6%	92.8%	3.13	0.0039	0.02
128	92.4	2.7	2.4	1.0	1.5	24531.87	90.1%	89.9%	92.8%	3.14	0.0039	0.02
129	92.2	2.7	2.4	1.2	1.5	24712.06	90.0%	89.8%	92.7%	3.18	0.0039	0.02
130	93.0	2.6	2.2	0.9	1.3	24891.36	90.9%	90.3%	94.0%	2.53	0.0040	0.02
131	92.5	2.7	2.3	1.1	1.4	25071.58	90.3%	89.8%	93.3%	2.49	0.0039	0.02
132	92.3	2.7	2.3	1.3	1.4	25251.83	90.3%	89.8%	93.4%	2.51	0.0039	0.02
133	92.6	2.7	2.4	0.8	1.5	25431.81	90.0%	89.7%	93.0%	2.47	0.0039	0.02
134	92.4	2.7	2.4	1.0	1.5	25611.99	90.0%	89.8%	93.0%	2.58	0.0039	0.02


Average Reaction Efficiencies *ECM259013C & Engelhard Escat 326
Average Reaction Efficiencies
*ECM259013C & Engelhard Escat 326
Average Conversion Efficiency, %
100%
95%
90%
85%
80%
75%
70%
Control Malfunction
0
20
40
60
80
100
120
140
160
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *ECM259013C & Engelhard Escat 326
Average Reformate Composition
*ECM259013C & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
Mole % H2
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
0
20
40
60
80
100
120
140
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent *ECM259013C & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*ECM259013C & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
120
140
160
Cycle

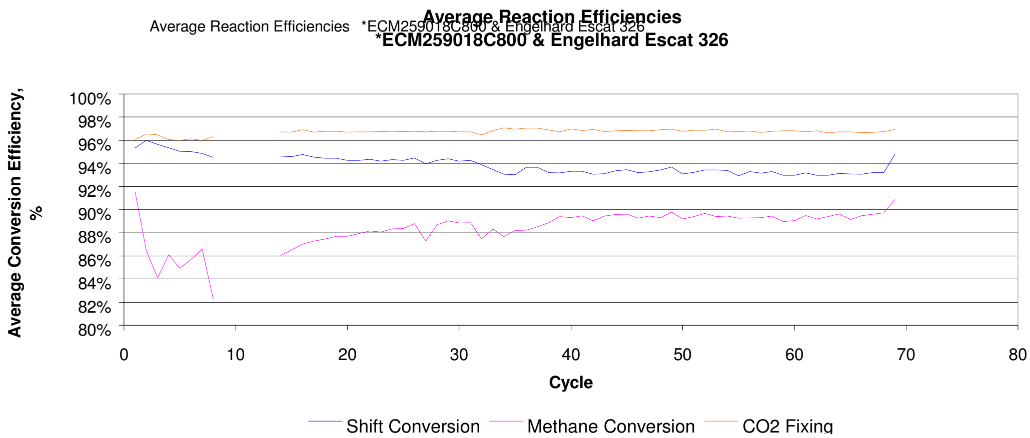
CO_2 Sorption Catalyst	*ECM259018C800
Reforming Catalyst: 0.5% rhodium or	Engelhard Escat 326
Composition CO_2 sorb	CaO/Al2O3 (90/10)
Binder	15%Al203
Batch No.	HCB203032A (030A+031A)
Extruded by	CSMP
Oven Atmosphere	N2
Calcined, C	800

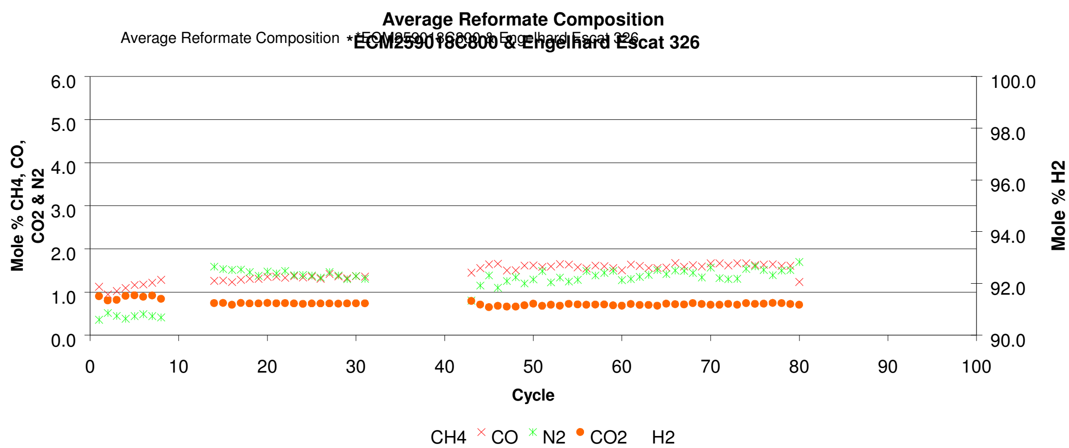
Wt. CO2 extrudate, g	23.04
Vol. CO2 extrudate, cc	32.5
Density CO2, g/cc	0.7
Wt. SMR Cat., g	4.5
Vol. SMR Cat., cc	7.5
Density SMR, g/cc	0.6
Total Bed Wt., g	27.54
Total Bed Vol., ml	40.0

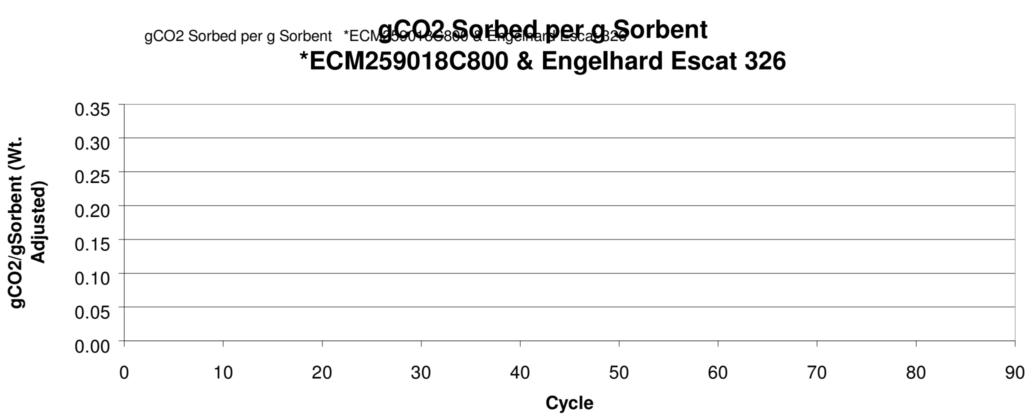
Reactor	R1
S/C	3
GHSV, hr-1	390
Reforming, °C	600
Calcination, °C	800
Pressure, atm.	1

Cycle	H2	CH4	CO	N2	CO2	M	WGS	CC	CF	Avg. Cycle Time	S	(Wt. Adjusted) gCO2 / gSorb
1	95.3	2.3	1.1	0.4	0.9	748.79	95.3%	91.5%	96.1%	29.67	0.0047	0.30
2	93.9	3.8	0.9	0.5	0.8	925.02	96.0%	86.4%	96.5%	25.97	0.0045	0.25
3	93.2	4.5	1.0	0.4	0.8	1103.23	95.6%	84.1%	96.5%	23.06	0.0044	0.22
4	93.7	3.9	1.1	0.4	0.9	1284.29	95.4%	86.1%	96.1%	24.37	0.0045	0.23
5	93.2	4.2	1.2	0.4	0.9	1463.84	95.1%	84.9%	96.0%	23.46	0.0044	0.22
6	93.4	4.0	1.2	0.5	0.9	1641.81	95.0%	85.7%	96.1%	22.09	0.0044	0.21
7	93.7	3.7	1.2	0.4	0.9	1821.32	94.8%	86.6%	96.0%	22.21	0.0045	0.21
8	92.3	5.1	1.3	0.4	0.8	2000.63	94.5%	82.2%	96.3%	20.02	0.0042	0.18
9												
10												
11												
12												
13												
14	92.6	3.8	1.3	1.6	0.7	2612.47	94.6%	86.0%	96.7%	18.23	0.0043	0.17
15	92.8	3.7	1.3	1.5	0.7	2792.32	94.6%	86.5%	96.7%	18.13	0.0044	0.17
16	93.0	3.5	1.2	1.5	0.7	2972.51	94.8%	87.0%	96.9%	17.83	0.0044	0.17
17	93.0	3.5	1.3	1.5	0.7	3152.22	94.5%	87.3%	96.7%	18.65	0.0044	0.17
18	93.1	3.4	1.3	1.5	0.7	3333.13	94.4%	87.5%	96.8%	18.75	0.0044	0.18
19	93.2	3.3	1.3	1.4	0.7	3512.73	94.5%	87.7%	96.8%	18.65	0.0044	0.18
20	93.1	3.3	1.4	1.5	0.7	3693.19	94.3%	87.7%	96.7%	19.31	0.0044	0.18
21	93.2	3.3	1.4	1.4	0.7	3872.90	94.2%	87.9%	96.7%	19.32	0.0044	0.18
22	93.2	3.2	1.3	1.5	0.7	4051.99	94.3%	88.2%	96.7%	18.17	0.0044	0.17
23	93.3	3.2	1.4	1.4	0.7	4232.41	94.2%	88.1%	96.7%	18.09	0.0044	0.17
24	93.4	3.1	1.3	1.4	0.7	4411.92	94.3%	88.3%	96.8%	17.69	0.0044	0.17
25	93.4	3.1	1.4	1.4	0.7	4591.43	94.2%	88.4%	96.7%	17.72	0.0044	0.17
26	93.6	3.0	1.3	1.3	0.7	4770.93	94.5%	88.8%	96.8%	16.51	0.0045	0.16
27	92.9	3.5	1.4	1.5	0.7	4952.41	94.0%	87.3%	96.7%	18.42	0.0044	0.17
28	93.5	3.0	1.4	1.4	0.7	5130.28	94.2%	88.7%	96.8%	16.63	0.0045	0.16
29	93.7	2.9	1.3	1.3	0.7	5309.73	94.4%	89.0%	96.8%	15.56	0.0045	0.15
30	93.5	3.0	1.4	1.4	0.7	5489.59	94.2%	88.9%	96.7%	15.66	0.0045	0.15
31	93.6	3.0	1.4	1.3	0.7	5669.17	94.3%	88.9%	96.7%	15.10	0.0045	0.14
43	93.6	3.4	1.4	0.8	0.8	5854.46	93.9%	87.5%	96.5%	10.54	0.0044	0.10
44	93.4	3.1	1.6	1.1	0.7	7825.09	93.4%	88.3%	96.8%	9.49	0.0044	0.09
45	93.0	3.3	1.6	1.4	0.6	8004.29	93.1%	87.7%	97.1%	10.44	0.0044	0.10
46	93.4	3.2	1.7	1.1	0.7	8185.36	93.0%	88.2%	96.9%	9.50	0.0044	0.09
47	93.4	3.2	1.5	1.3	0.7	8363.59	93.7%	88.2%	97.1%	9.51	0.0044	0.09
48	93.4	3.1	1.5	1.3	0.7	8543.74	93.7%	88.5%	97.0%	9.44	0.0044	0.09
49	93.5	3.0	1.6	1.2	0.7	8724.49	93.2%	88.9%	96.9%	9.21	0.0044	0.09
50	93.5	2.8	1.6	1.3	0.7	8904.02	93.2%	89.4%	96.7%	9.50	0.0044	0.09
51	93.4	2.9	1.6	1.5	0.7	9084.00	93.3%	89.3%	97.0%	9.46	0.0045	0.09
52	93.7	2.8	1.6	1.2	0.7	9263.98	93.3%	89.5%	96.8%	8.93	0.0045	0.08
53	93.4	2.9	1.6	1.3	0.7	9444.22	93.0%	89.0%	96.9%	9.08	0.0044	0.09
54	93.6	2.8	1.6	1.2	0.7	9623.81	93.1%	89.5%	96.8%	8.98	0.0044	0.09
55	93.6	2.8	1.6	1.3	0.7	9803.74	93.4%	89.6%	96.8%	8.74	0.0045	0.08
56	93.5	2.8	1.5	1.5	0.7	9982.96	93.5%	89.6%	96.8%	9.06	0.0045	0.09
57	93.4	2.9	1.6	1.4	0.7	10163.53	93.2%	89.3%	96.8%	8.87	0.0044	0.08
58	93.4	2.8	1.6	1.4	0.7	10342.89	93.3%	89.4%	96.8%	9.00	0.0045	0.09
59	93.4	2.9	1.6	1.5	0.7	10522.80	93.4%	89.3%	96.9%	8.45	0.0045	0.08
60	93.8	2.7	1.5	1.3	0.7	10702.64	93.7%	89.8%	97.0%	8.31	0.0045	0.08
61	93.4	2.9	1.6	1.3	0.7	10883.28	93.1%	89.2%	96.8%	8.38	0.0044	0.08
62	93.5	2.8	1.6	1.4	0.7	11063.24	93.2%	89.4%	96.9%	7.95	0.0044	0.08
63	93.6	2.7	1.6	1.4	0.7	11242.63	93.4%	89.7%	96.9%	8.33	0.0045	0.08
64	93.4	2.8	1.6	1.5	0.7	11422.53	93.4%	89.4%	96.9%	7.87	0.0045	0.07
65	93.5	2.8	1.6	1.4	0.7	11602.18	93.4%	89.4%	96.7%	7.86	0.0045	0.07
66	93.2	2.9	1.7	1.5	0.7	11782.85	92.9%	89.3%	96.8%	8.34	0.0044	0.08
67	93.3	2.9	1.6	1.5	0.7	11961.91	93.3%	89.3%	96.8%	7.84	0.0044	0.07
68	93.3	2.9	1.6	1.4	0.7	12142.40	93.1%	89.3%	96.7%	7.76	0.0044	0.07
69	93.5	2.8	1.6	1.3	0.7	12322.24	93.3%	89.4%	96.8%	7.79	0.0045	0.07
70	93.1	3.0	1.7	1.6	0.7	12502.46	93.0%	88.9%	96.8%	8.15	0.0044	0.08
71	93.4	2.9	1.7	1.3	0.7	12682.45	93.0%	89.1%	96.8%	7.85	0.0044	0.07
72	93.5	2.8	1.6	1.3	0.7	12862.50	93.2%	89.5%	96.7%	7.31	0.0044	0.07
73	93.4	2.9	1.7	1.3	0.7	13042.28	93.0%	89.2%	96.8%	7.72	0.0044	0.07
74	93.2	2.8	1.7	1.5	0.7	13222.01	93.0%	89.4%	96.6%	7.79	0.0044	0.07
75	93.3	2.8	1.6	1.6	0.7	13402.12	93.1%	89.6%	96.7%	7.55	0.0045	0.07
76	93.2	2.9	1.6	1.5	0.7	13581.85	93.1%	89.2%	96.7%	7.54	0.0044	0.07
77	93.4	2.8	1.6	1.4	0.7	13762.19	93.1%	89.5%	96.6%	7.03	0.0044	0.07
78	93.4	2.8	1.6	1.5	0.7	13941.52	93.2%	89.6%	96.7%	7.35	0.0045	0.07
79	93.4	2.7	1.6	1.5	0.7	14121.84	93.2%	89.7%	96.8%	7.26	0.0045	0.07
80	94.0	2.4	1.2	1.7	0.7	14300.71	94.8%	90.9%	96.9%	5.56	0.0046	0.05

Note: Cycles 1-14 methane regulator pressure onot adjusted correctly. Flow rates incorrect/ Combined with 9/12/05
12/6 - 12/7/05 (12 cycles lost during mass spec repair.)


Average Reaction Efficiencies *ECM259018C800 & Engelhard Escat 326
Average Reaction Efficiencies
*ECM259018C800 & Engelhard Escat 326
Average Conversion Efficiency, %
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
0
10
20
30
40
50
60
70
80
Cycle
Shift Conversion
Methane Conversion
CO2 Fixing


Average Reformate Composition *ECM259018C800 & Engelhard Escat 326
Average Reformate Composition
*ECM259018C800 & Engelhard Escat 326
Mole % CH4, CO, CO2 & N2
6.0
5.0
4.0
3.0
2.0
1.0
0.0
100.0
98.0
96.0
94.0
92.0
90.0
Mole % H2
0
10
20
30
40
50
60
70
80
90
100
Cycle
CH4
CO
N2
CO2
H2


gCO2 Sorbed per g Sorbent *ECM259018C800 & Engelhard Escat 326
gCO2 Sorbed per g Sorbent
*ECM259018C800 & Engelhard Escat 326
gCO2/gSorbent (Wt. Adjusted)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
90
Cycle

APPENDIX G

CaO Determination Comparison

CTV Lab Muffle Furnace Method Vs. CSMP CO2-TGA Method

CTV Lab Muffle Furnace Method

1. Individually weigh 4 clean crucibles on a calibrated analytical balance. Determine WEIGHT 1.
2. Place the clean, dry & weighed crucibles in the muffle furnace at 550C for 1 hour.
3. Cool in desiccator. Determine WEIGHT 2.
4. Place approximately 1 gram of sample in the crucible.
5. Determine WEIGHT 3.
6. *Dehydration*: Place the sample in the muffle furnace for 2 hours at 200C to drive off water.
7. Cool in desiccator. Determine WEIGHT 4.
8. *Decomposition*: Place the sample in the muffle furnace for 2 hours at 550C to determine the weight loss due to conversion from CaC2O4 to CaCO3. Cool in desiccator. Determine WEIGHT 5.
9. *Decarbonation*: Place samples in muffle furnace at 925C for 4 hours to determine the weight loss due to conversion of CaCO3 to CaO. Cool in desiccator. Determine WEIGHT 6.

Sample ID	ECM25-5061C300	ECM25-5061C500	ECM25-5061C750	ECM25-5061C800
WEIGHT 1 (Weight of clean crucible)	13.8211	13.4467	14.0251	14.6533
WEIGHT 2 (Crucible / 550C 1 hour)	13.8205	13.4463	14.0179	14.6533
WEIGHT 3 (Crucible + sample)	14.8787	14.4855	15.0398	15.6666
WEIGHT 4 (Crucible + sample 200C)	14.8775	14.4887	15.0635	15.7143
WEIGHT 5 (Crucible + CaC2O4)	14.8229	14.4679	15.0141	15.6371
WEIGHT 6 (Crucible + CaO)	14.5323	14.1713	14.8521	15.6177
Calcination Temp, C	300	500	750	800
Water and Organic Mat'l on Crucible, mg	0.6	0.4	7.2	0
Initial Sample Weight, g	1.0582	1.0392	1.0219	1.0133
Final Sample Weight, g	0.7118	0.725	0.8342	0.9644
Muffle Furnace Total Weight Loss, %	32.73%	30.23%	18.37%	4.83%
CSMP Results using CO2TGA				
Mass Loss, %	32.60%	31.10%	15.60%	4.90%

Variation, %	+/-0.2%	+/-1.4%	+/-1.0%	+/-0.2%
CSMP CO2TGA/CTV Muffle Furnace	1.00	1.03	0.85	1.02

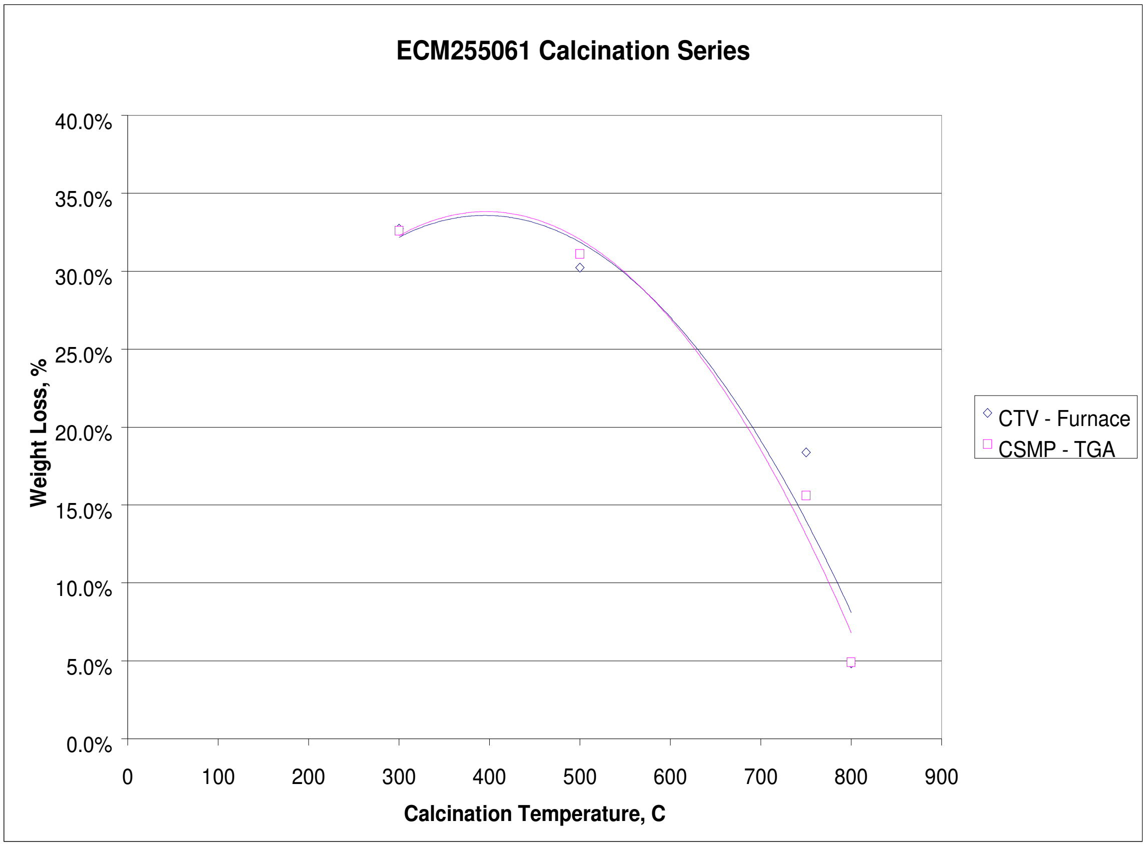


Figure A-1. Percent weight loss as a function of calcination temperature.

APPENDIX H

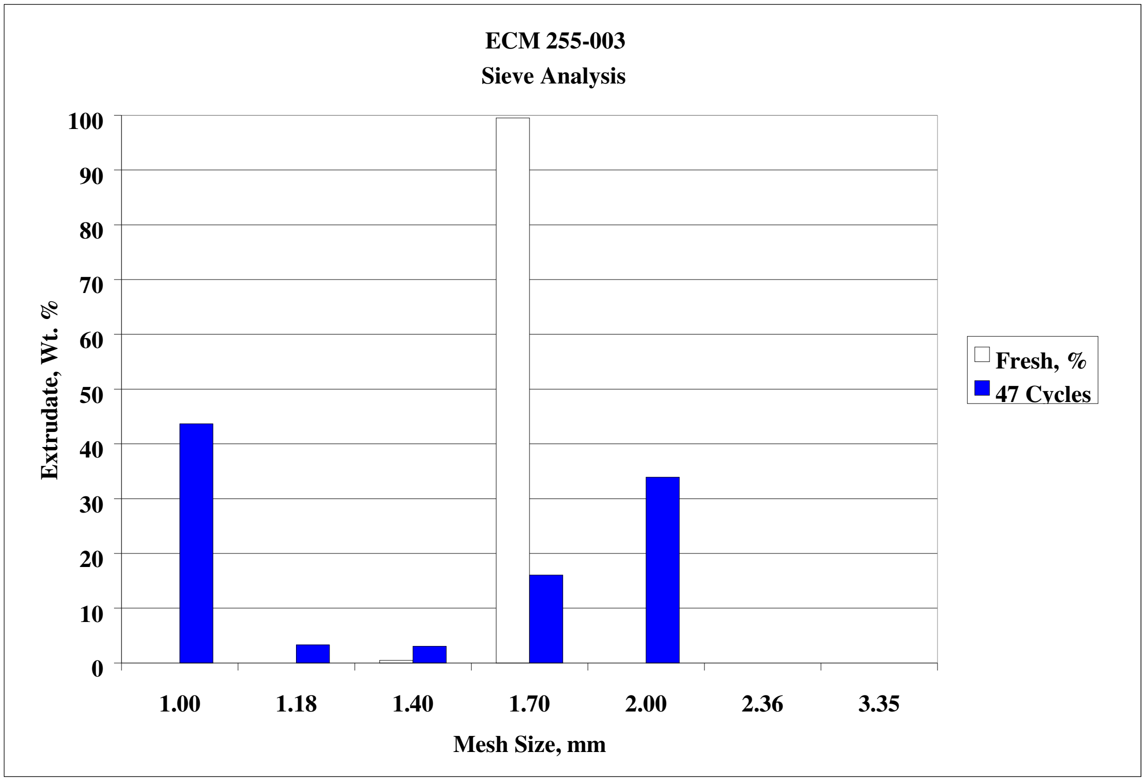
CO_2 Sorption Catalyst	ECM 255-003	ECM 255-008	ECM 255-019
Reforming Catalyst	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)
Reactor	1	1	1
Date loaded	2/24/2005	5/9/2005	1/10/2005
Date unloaded	3/3/2005	5/19/2005	1/14/2005
Composition CO_2 sorb	CaO (100)	CaO/MgO (80/20)	CaO/Al2O3 (95/5)
SMP + Binder	SMP Comp + 15%Al203	SMP Comp + 15%Al203	SMP Comp + 15%Al203
Batch No.		HCM178177E + HCM178178A	PCB953401A-1
Cycles	47	81	30
Calcined (Air), °C	750	750	750
Sieve Analysis- Fresh			
Sample Through (Mesh), g	**g**	**g**	**g**
18	0.00	0.00	0.00
16	0.00	0.00	0.00
14	0.05	0.03	0.00
12	10.20	9.99	10.08
10	0.00	0.00	0.00
8	0.00	0.00	0.00
6	0.00	0.00	0.00
Total	10.25	10.02	10.08
Fresh, %			
Mesh Size, mm			
1.00	0	0	0
1.18	0	0	0
1.40	0	0	0
1.70	100	100	100
2.00	0	0	0
2.36	0	0	0
3.35	0	0	0
Total	100	100	100
Sieve Analysis-Used			
Sample Through (Mesh), g	**g**	**g**	**g**
18	14.54	2.82	1.47
16	1.09	0.37	0.64
14	1.02	0.33	0.47
12	5.35	17.76	20.41
10	11.30	0.00	0.00
8	0.00	0.00	0.00
6	0.00	0.00	0.00
Total	33.30	21.28	22.99
%Fines	46.94	14.99	9.18
Mesh Size, mm	47 Cycles	81 cycles	30 Cycles
1.00	44	13	6
1.18	3	2	3
1.40	3	2	2
1.70	16	83	89
2.00	34	0	0
2.36	0	0	0
3.35	0	0	0
Total	100.00	100.00	100.00
Comments	Mixed with SMR & Carbon		

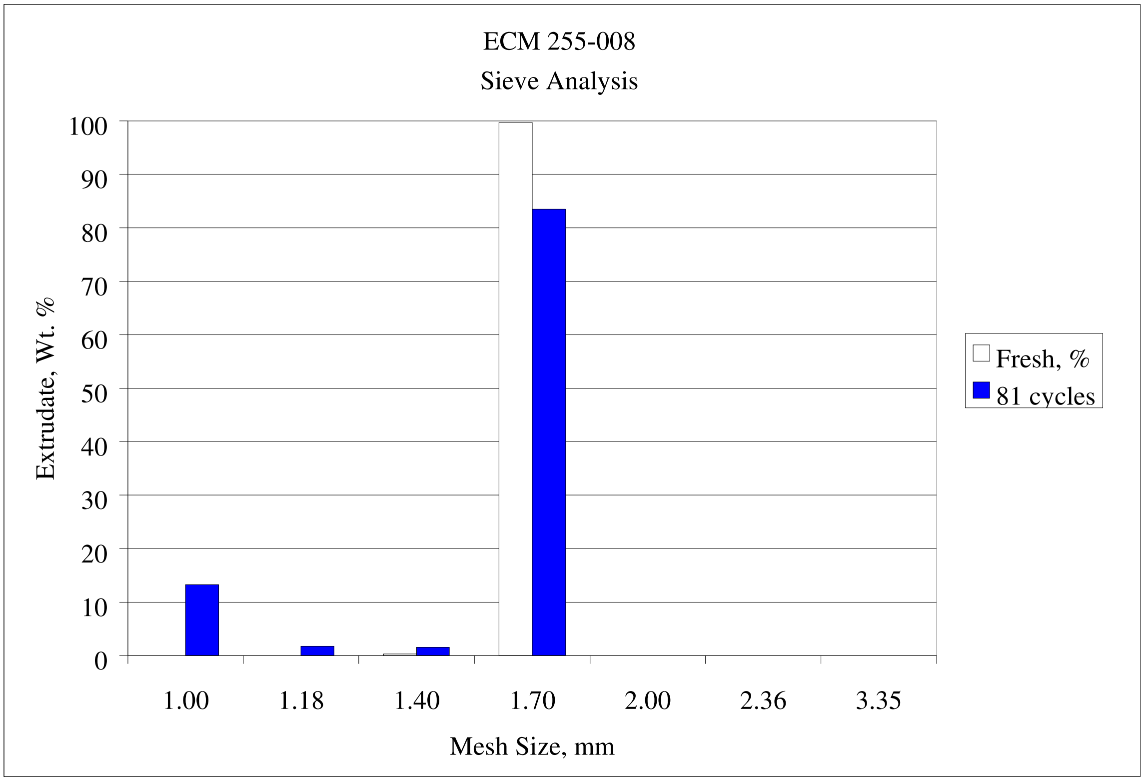
CO_2 Sorption Catalyst	ECM 255-021	*ECM 255-029	*ECM255-036
Reforming Catalyst	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)
Reactor	2	1	2
Date loaded	1/10/2005	3/28/2005	5/4/2005
Date unloaded	1/14/2005	4/11/2005	5/22/2005
Composition CO_2 sorb	CaO/Al2O3 (90/10)	*CaO-Al203 (95/5)	*CaO-Al203 (90/10)
SMP + Binder	SMP Comp + 10%Al203	SMP Comp.+ 15% Al2O3	SMP Comp.+ 15% Al2O3
Batch No.	PCB954103A-1	No information available	ECM255032 + ECM255033
Cycles	30	37	81
Calcined (Air), °C	750	750	750
Sieve Analysis- Fresh			
Sample Through (Mesh), g	**g**	**g**	**g**
18	0.00	0.00	0.00
16	0.00	0.00	0.00
14	0.25	0.09	0.04
12	9.74	6.35	27.00
10	0.00	0.12	0.00
8	0.00	0.46	0.00
6	0.00	2.98	0.00
Total	9.99	10.00	27.04
Fresh, %			
Mesh Size, mm			
1.00	0	0	0
1.18	0	0	0
1.40	3	1	0
1.70	97	64	100
2.00	0	1	0
2.36	0	5	0
3.35	0	30	0
Total	100	100	100
Sieve Analysis-Used			
Sample Through (Mesh), g	**g**	**g**	**g**
18	0.19	1.36	1.03
16	0.04	0.36	2.13
14	0.23	0.59	19.98
12	1.97	17.00	0.00
10	18.52	0.31	0.00
8	0.00	0.52	0.00
6	0.00	4.50	0.00
Total	20.95	24.64	23.14
%Fines	1.10	6.98	13.66
Mesh Size, mm	30 Cycles	37 Cycles	81 Cycles
1.00	1	6	4
1.18	0	1	9
1.40	1	2	86
1.70	9	69	0
2.00	88	1	0
2.36	0	2	0
3.35	0	18	0
Total	100.00	100.00	100.00
Comments			Restarted 5/9/05

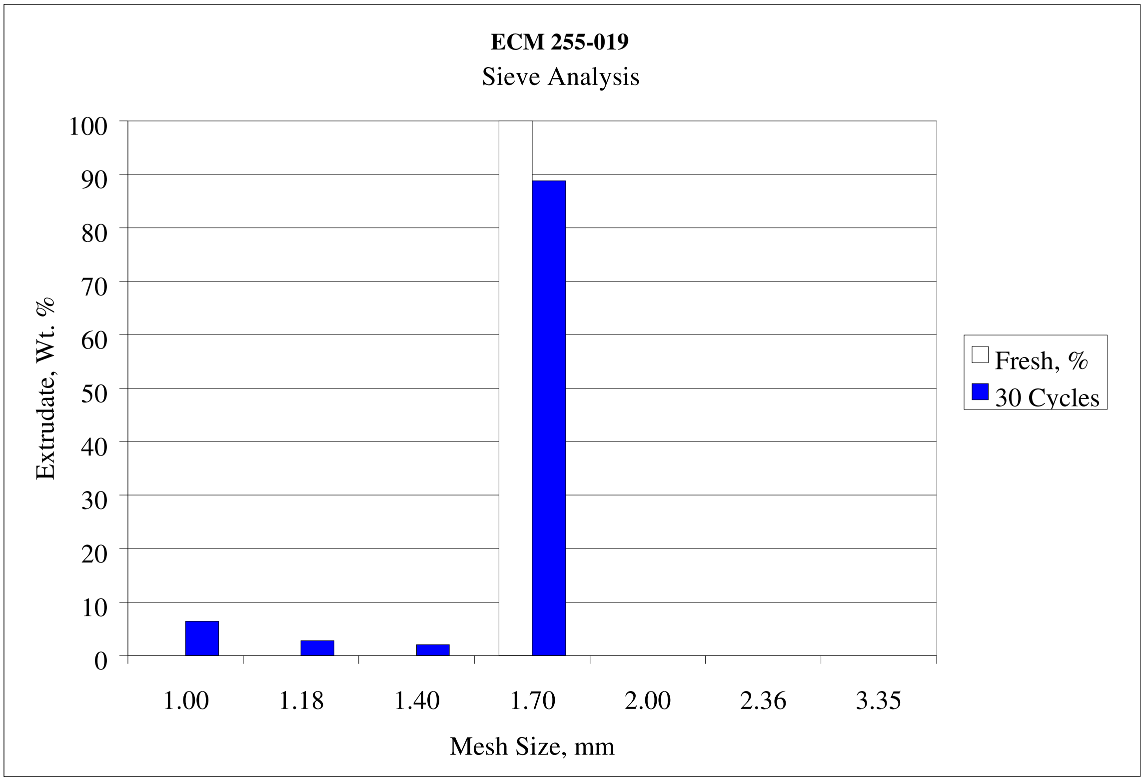
CO_2 Sorption Catalyst	ECM255-061C300	ECM255-061C500	ECM255-061C750
Reforming Catalyst	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)
Reactor	1	2	1
Date loaded	5/19/2005	6/8/2005	6/21/2005
Date unloaded	5/29/2005	6/15/2005	
Composition CO_2 sorb	*CaO-Al203 (90/10)	*CaO-Al203 (90/10)	*CaO-Al203 (90/10)
SMP + Binder	SMP Comp.+ 15% Al2O3	SMP Comp.+ 15% Al2O3	SMP Comp.+ 15% Al2O3
Batch No.	T-Storm	PCB954103A-1(HCB198078B +	
Cycles	75	57	81
Calcined (Air), °C	300	500	750
Sieve Analysis- Fresh			
Sample Through (Mesh), g	g	g	g
18	0.00	0.00	0.00
16	0.04	0.01	0.00
14	0.03	0.00	0.00
12	6.22	6.65	3.00
10	0.07	0.19	0.00
8	0.37	1.49	0.84
6	1.06	0.00	0.00
Total	7.79	8.34	3.84
Fresh, %			
Mesh Size, mm			
1.00	0	0	0
1.18	1	0	0
1.40	0	0	0
1.70	80	80	78
2.00	1	2	0
2.36	5	18	22
3.35	14	0	0
Total	100	100	100
Sieve Analysis-Used			
Sample Through (Mesh), g	g	g	g
18	4.00	0.56	4.92
16	3.79	0.22	1.13
14	1.71	1.37	0.02
12	18.17	17.36	11.52
10	1.38	0.88	0.83
8	0.00	2.18	2.31
6	1.06	0.15	0.00
Total	30.11	22.72	20.73
%Fines	25.87	3.43	29.18
Mesh Size, mm	75 Cycles	57 Cycles	81 Cycles
1.00	13	2	24
1.18	13	1	5
1.40	6	6	0
1.70	60	76	56
2.00	5	4	4
2.36	0	10	11
3.35	4	1	0
Total	100.00	100.00	100.00
Comments		Cycles 23-30: Preheater Failure	

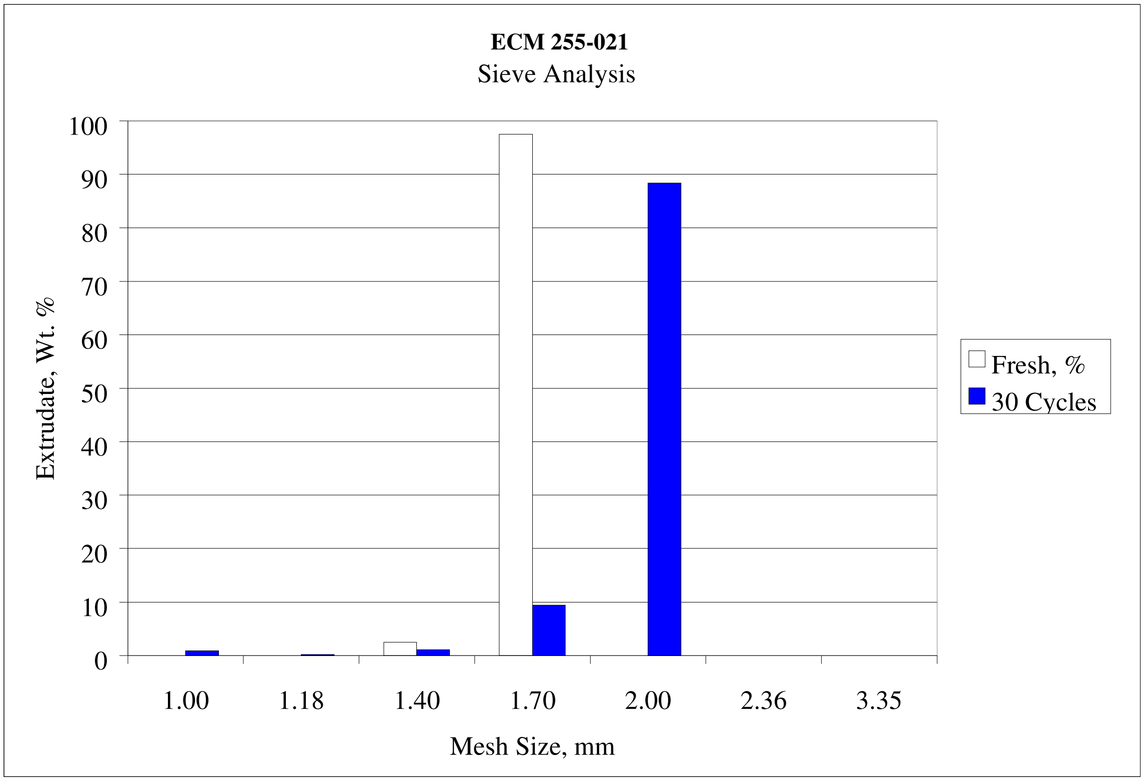
CO_2 Sorption Catalyst	ECM255-061C800	ECM259-002-2C	ECM259-011C
Reforming Catalyst	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)
Reactor	1	1	2
Date loaded	7/5/2005	6/8/2005	6/21/2005
Date unloaded	7/15/2005	6/20/2005	6/30/2005
Composition CO_2 sorb	CaO-Al203 (90/10)	CaO-Al203 (90/10)	CaO-Al203 (90/10)
SMP + Binder	SMP Comp.+ 15% Al2O3	SMP Comp.+ 15% Al2O3	SMP Comp.+ 15% Al2O3
Batch No.	PCB954103A-1(HCB198078B +	PCB290040C (HCB203020A)	
Cycles	74	53	77
Calcined (Air), °C	800	750	750
Sieve Analysis- Fresh			
Sample Through (Mesh), g	**g**	**g**	**g**
18	0.00	0.00	0.00
16	0.00	0.08	0.00
14	0.03	0.05	0.00
12	8.33	9.96	5.89
10	0.20	0.00	0.33
8	1.53	0.00	0.45
6	0.00	0.00	3.77
Total	10.09	10.09	10.44
Fresh, %			
Mesh Size, mm			
1.00	0	0	0
1.18	0	1	0
1.40	0	0	0
1.70	83	99	56
2.00	2	0	3
2.36	15	0	4
3.35	0	0	36
Total	100	100	100
Sieve Analysis-Used			
Sample Through (Mesh), g	**g**	**g**	**g**
18	1.92	0.15	0.00
16	0.36	0.19	0.35
14	3.68	1.64	4.96
12	14.96	21.42	1.00
10	0.67	0.00	9.70
8	1.52	0.00	2.36
6	2.74	0.00	4.80
Total	25.85	23.40	23.17
%Fines	8.82	1.45	1.51
Mesh Size, mm	74 Cycles	53 Cycles	77 Cycles
1.00	7	1	0
1.18	1	1	2
1.40	14	7	21
1.70	58	92	4
2.00	3	0	42
2.36	6	0	10
3.35	11	0	21
Total	100.00	100.00	100.00
Comments			

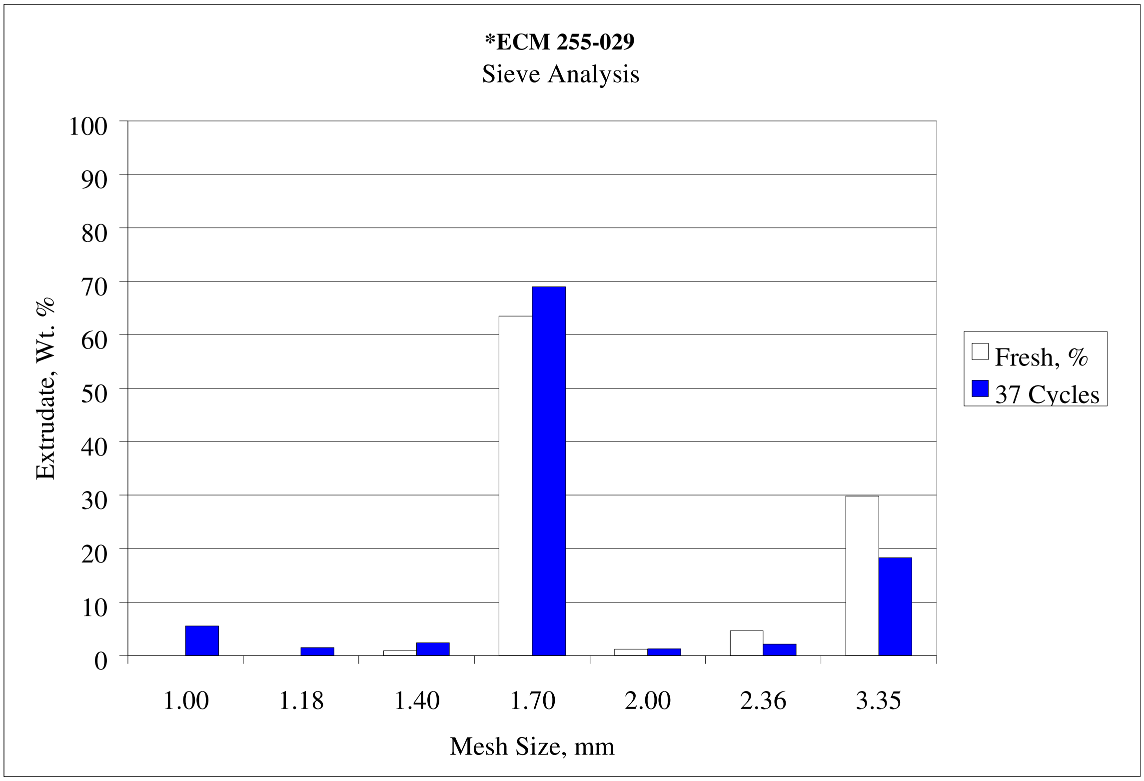
CO_2 Sorption Catalyst	*ECM259-012C	*ECM259-013C	*ECM259-013C	*ECM259-018C800
Reforming Catalyst	Engelhard 326 (0.5%Rh on Alumina)	Engelhard SR55	Engelhard 326 (0.5%Rh on Alumina)	Engelhard 326 (0.5%Rh on Alumina)
Reactor	2	1	2	2
Date loaded	7/5/2005	8/4/2005	8/4/2005	9/9/2005
Date unloaded	7/15/2005	8/22/2005	8/22/2005	10/6/2005
Composition CO_2 sorb	CaO-Al203 (90/10)	CaO/Al2O3 (90/10)	CaO/Al2O3 (90/10)	CaO/Al2O3 (90/10)
SMP + Binder	SMP Comp.+ 15% Al2O3	SMP Comp.+ 15% Al2O3	SMP Comp.+ 15% Al2O3	SMP Comp.+ 15% Al2O3
Batch No.	ECM259007-009			HCB203032A (030A+031A)
Cycles	77	113	113	180
Calcined (Air), °C	750	750	750	800
Sieve Analysis- Fresh				
Sample Through (Mesh), g	g	g	g	g
18	0.03	0.00	0.00	0.00
16	0.02	0.03	0.03	0.02
14	0.02	0.02	0.02	0.03
12	5.94	6.64	6.64	2.27
10	0.27	0.37	0.37	2.26
8	0.76	2.71	2.71	5.90
6	2.61	0.36	0.36	0.15
Total	9.65	10.13	10.13	10.63
Fresh. %				
Mesh Size, mm				
1.00	0	0	0	0
1.18	0	0	0	0
1.40	0	0	0	0
1.70	62	66	66	21
2.00	3	4	4	21
2.36	8	27	27	56
3.35	27	4	4	1
Total	100	100	100	100
Sieve Analysis-Used				
Sample Through (Mesh), g	g	g	g	g
18	1.71	1.95	0.00	0.00
16	0.50	0.35	0.17	0.36
14	3.43	2.78	1.34	3.68
12	11.44	10.63	3.80	14.96
10	0.93	2.60	2.44	0.67
8	1.91	1.28	2.82	1.52
6	1.87	4.21	5.34	2.74
Total	21.79	23.80	15.91	23.93
%Fines	10.14	9.66	1.07	1.50
Mesh Size, mm	77 Cycles	113 Cycles	113 Cycles	180 Cycles
1.00	8	8	0	0
1.18	2	1	1	2
1.40	16	12	8	15
1.70	53	45	24	63
2.00	4	11	15	3
2.36	9	5	18	6
3.35	9	18	34	11
Total	100.00	100.00	100.00	100.00
Comments		Simulated Aging (22 Cycles)	Simulated Aging (22 Cycles)	

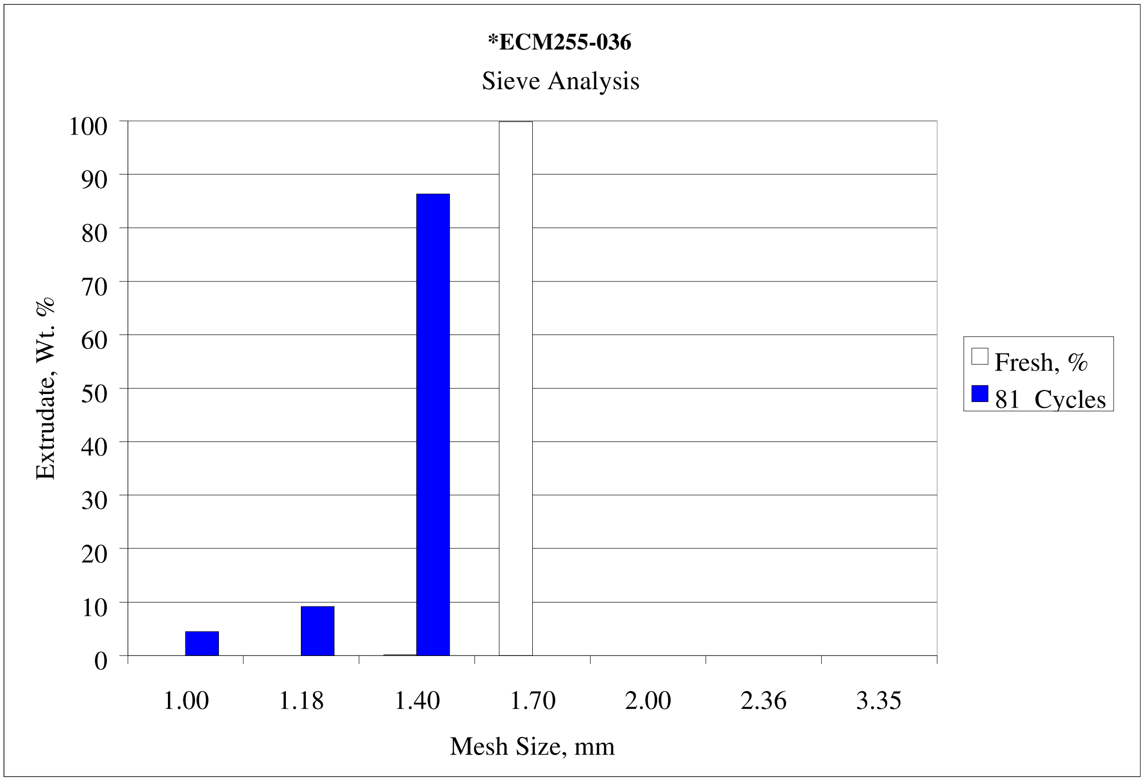

ECM 255-003
Sieve Analysis
100
90
80
70
60
50
40
30
20
10
0
Extrudate, Wt. %
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
47 Cycles

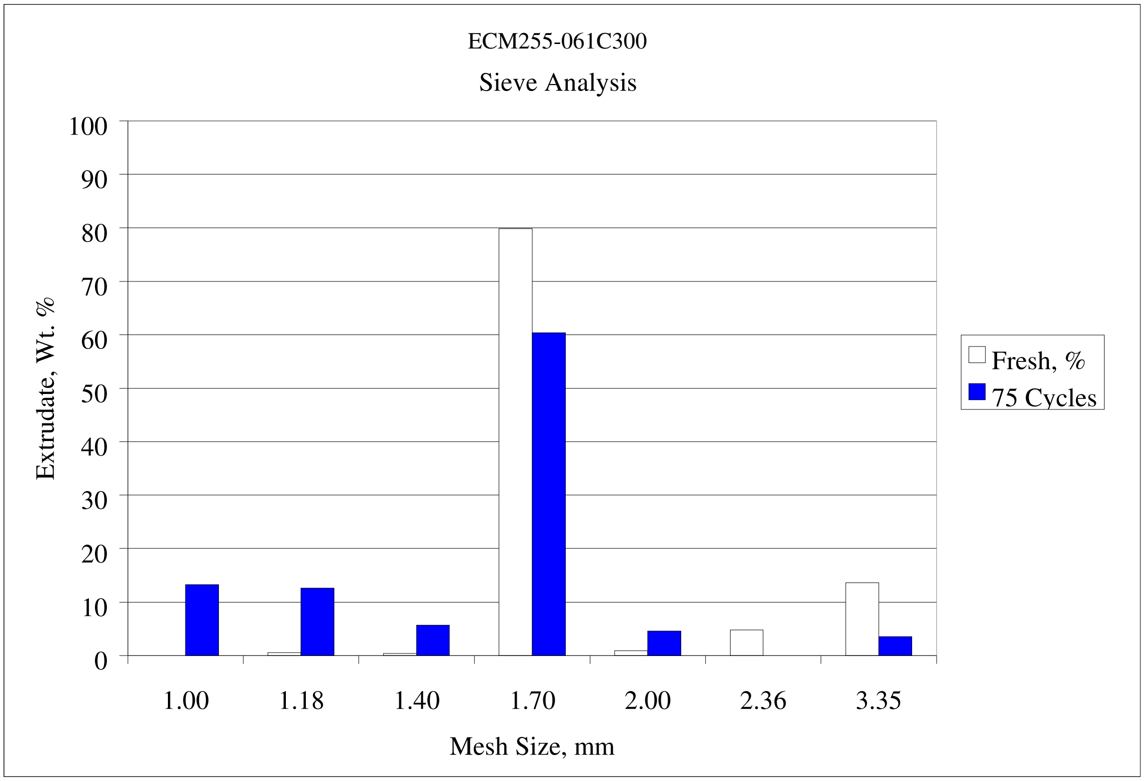

ECM 255-008
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
81 cycles

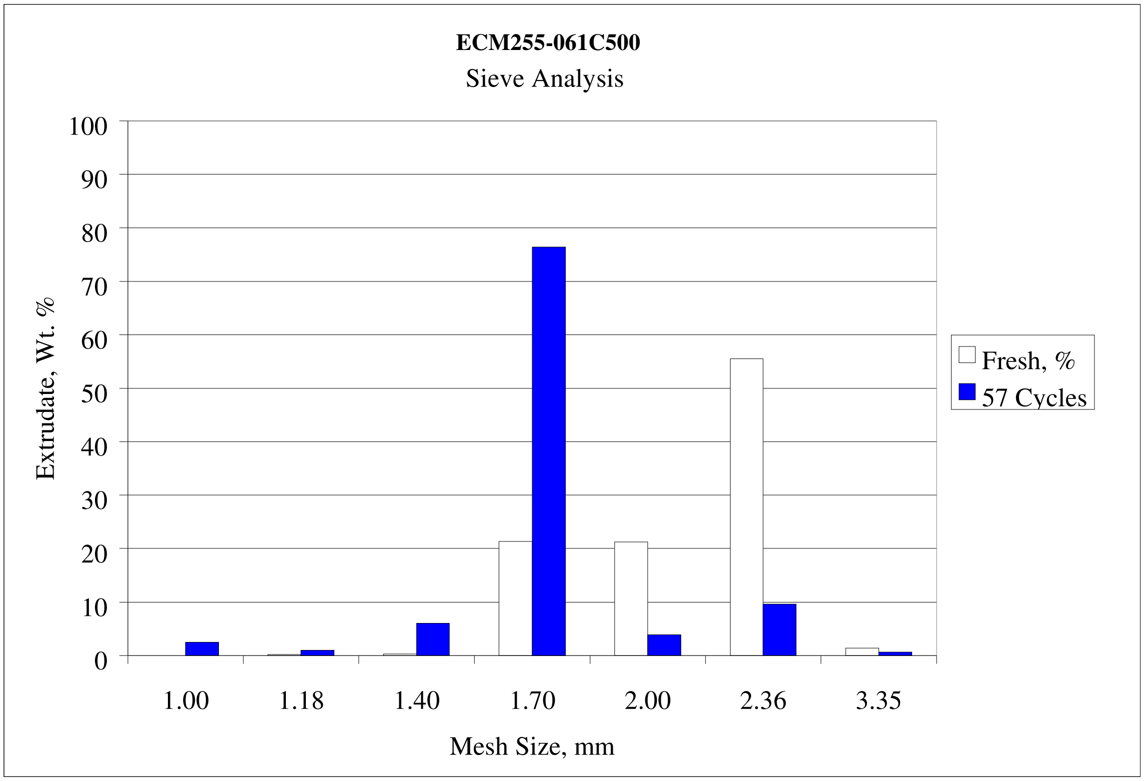

ECM 255-019
Sieve Analysis
100
90
80
70
60
50
40
30
20
10
0
Extrudate, Wt. %
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
30 Cycles

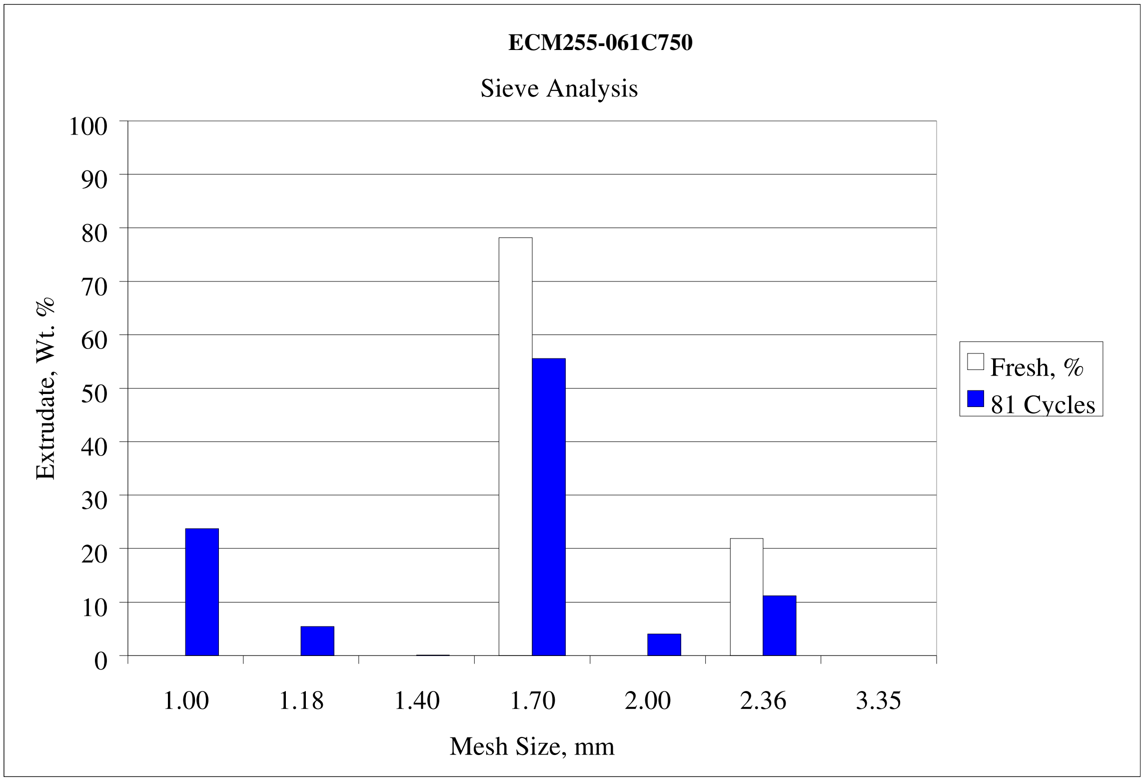

ECM 255-021
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
30 Cycles

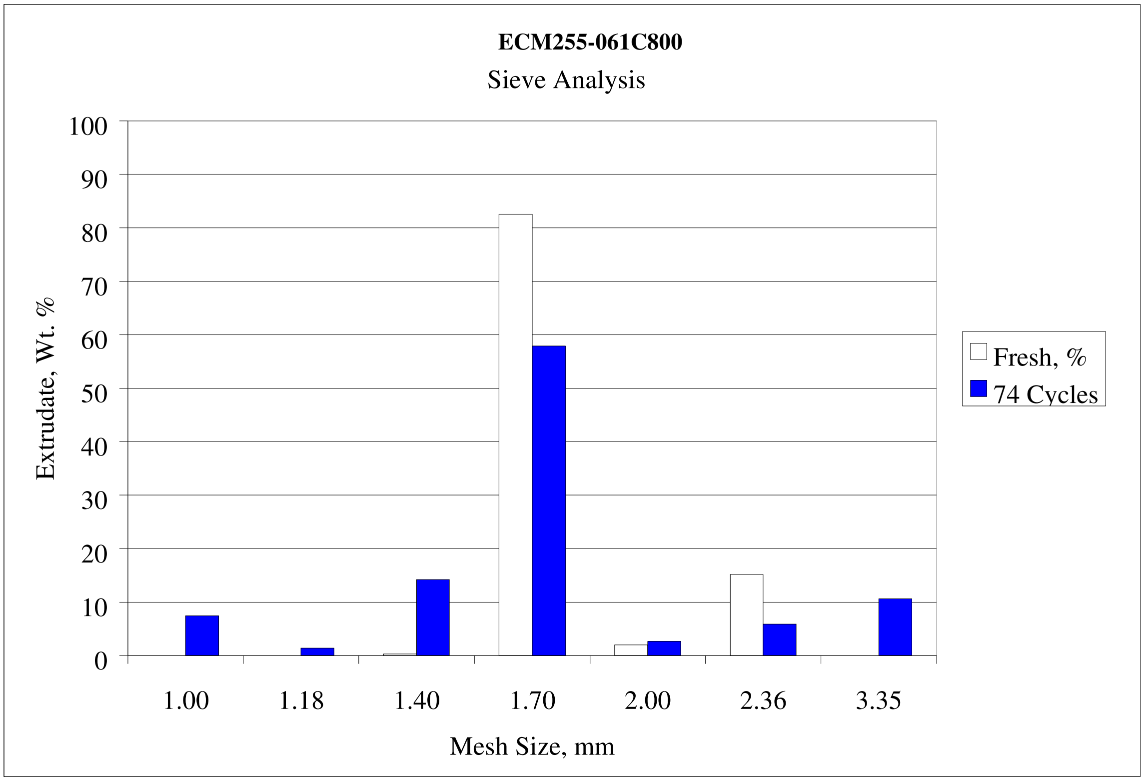

*ECM 255-029
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
37 Cycles

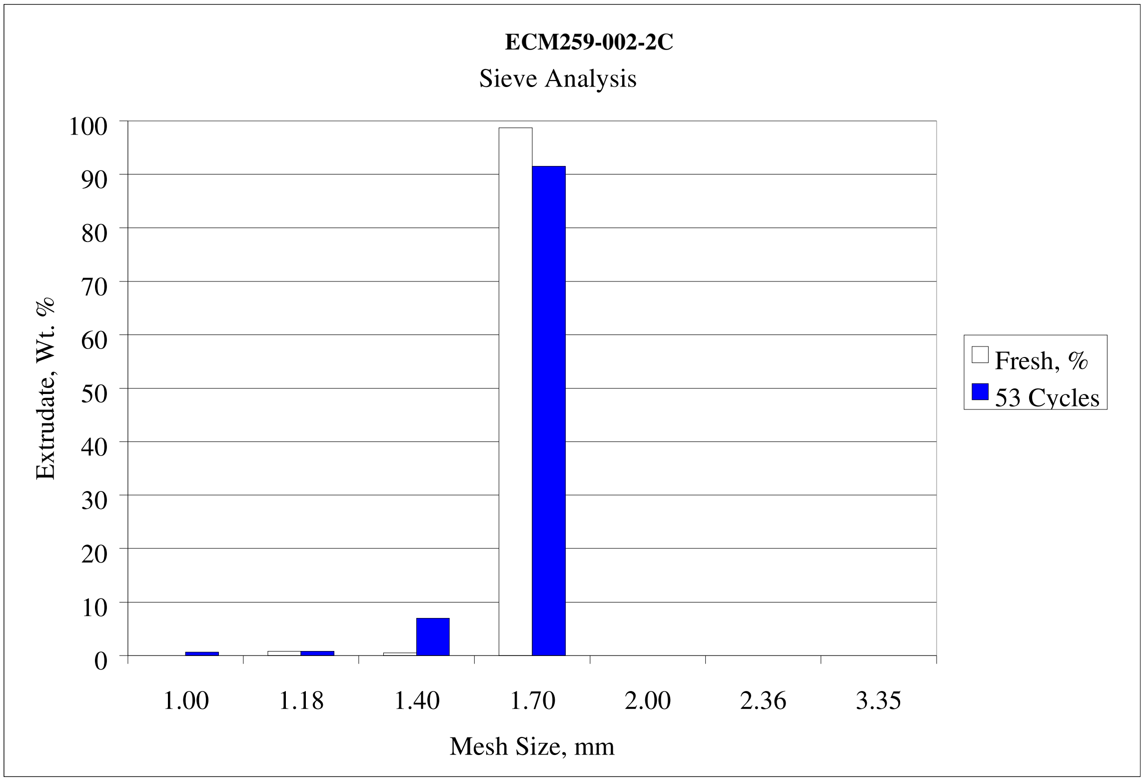

*ECM255-036
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
81 Cycles

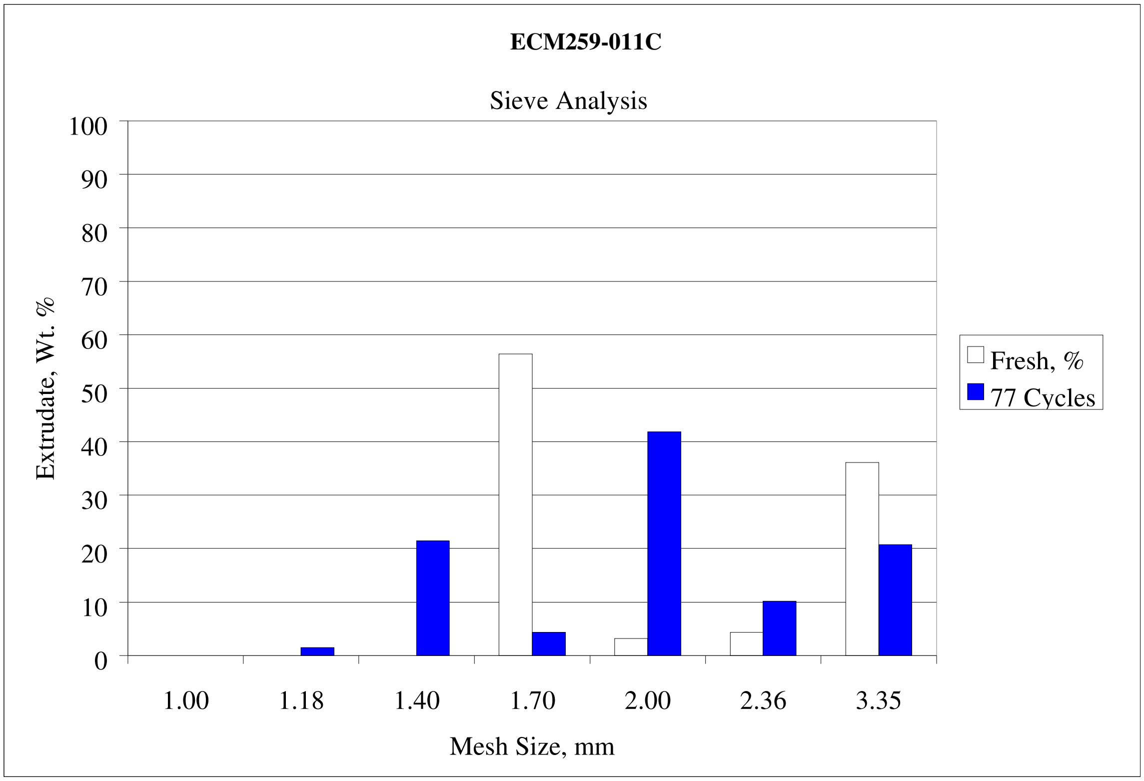

ECM255-061C300
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
75 Cycles

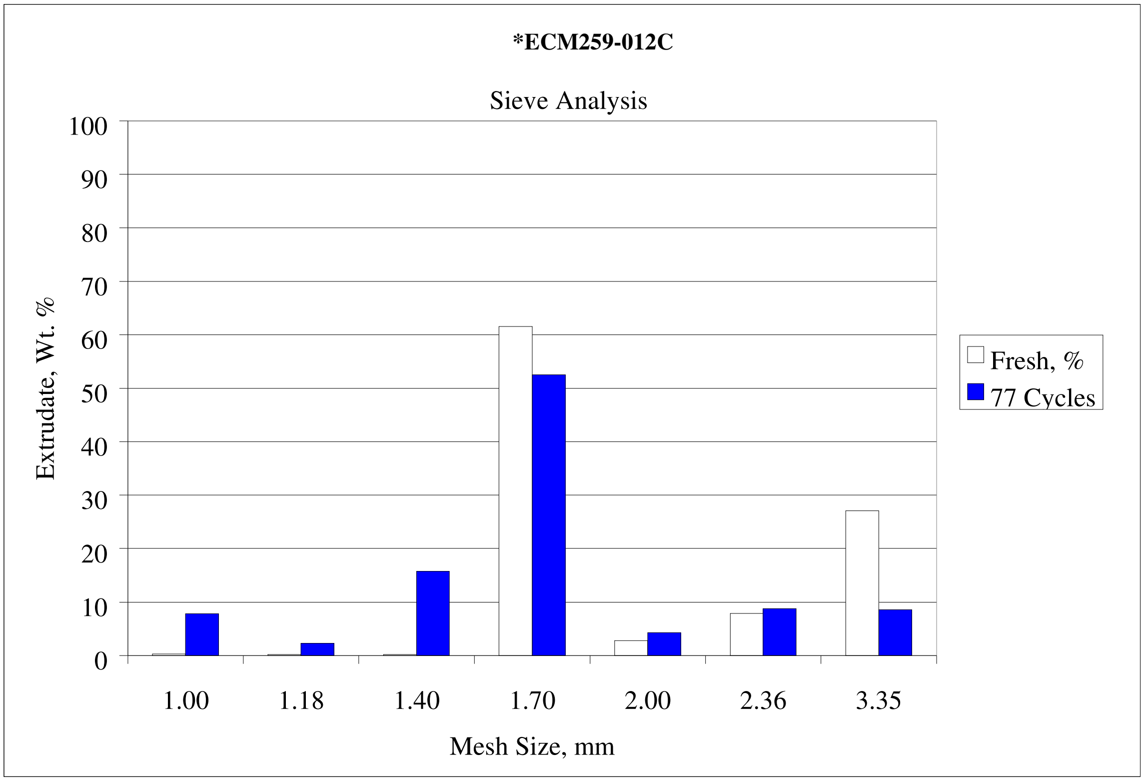

ECM255-061C500
Sieve Analysis
100
90
80
70
60
50
40
30
20
10
0
Extrudate, Wt. %
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
57 Cycles

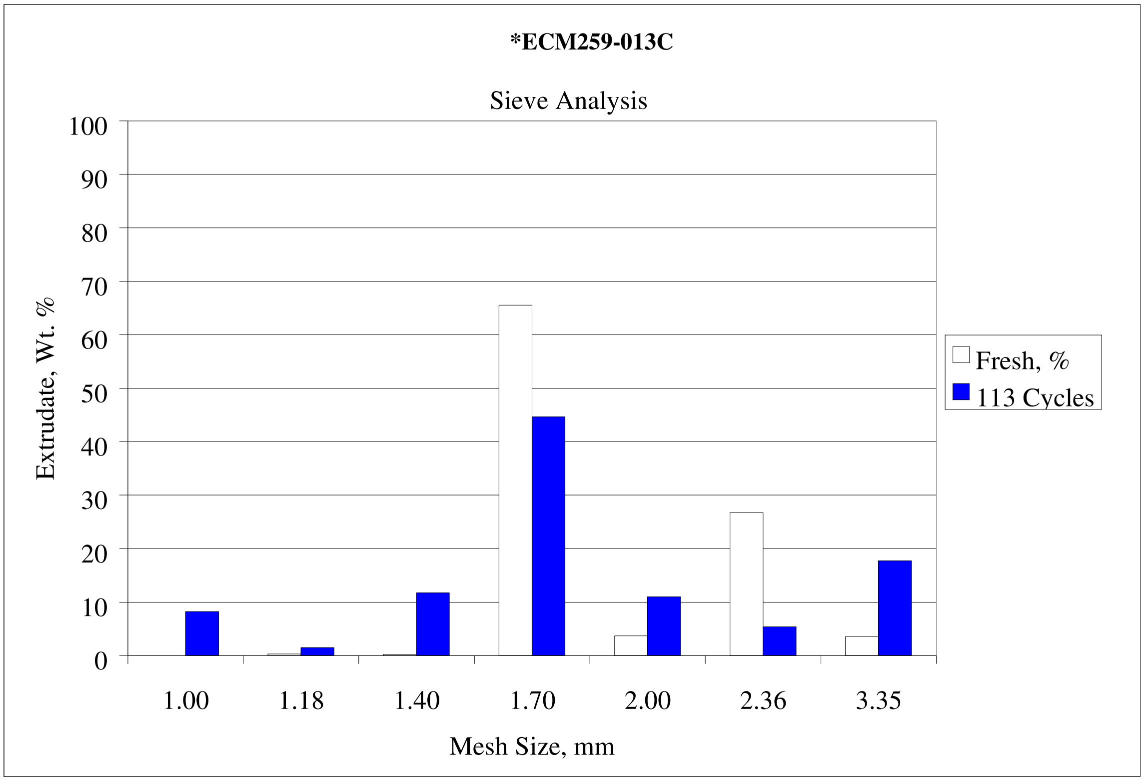

ECM255-061C750
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
81 Cycles

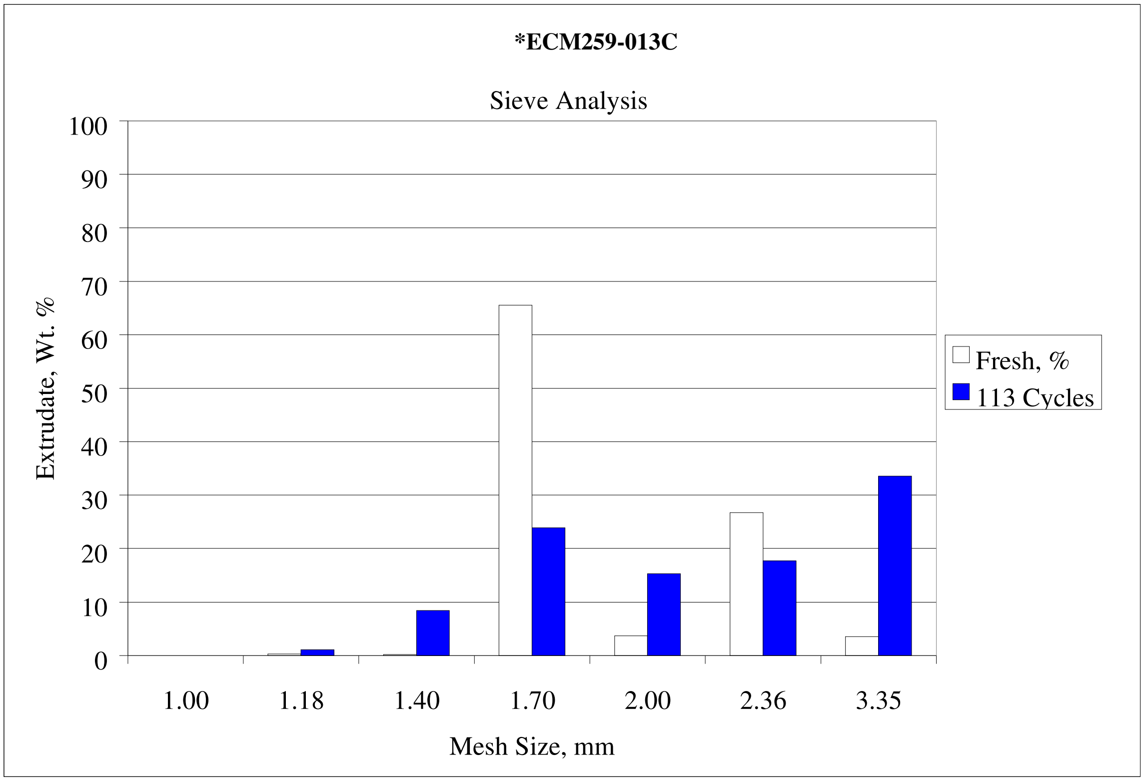

ECM255-061C800
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
74 Cycles

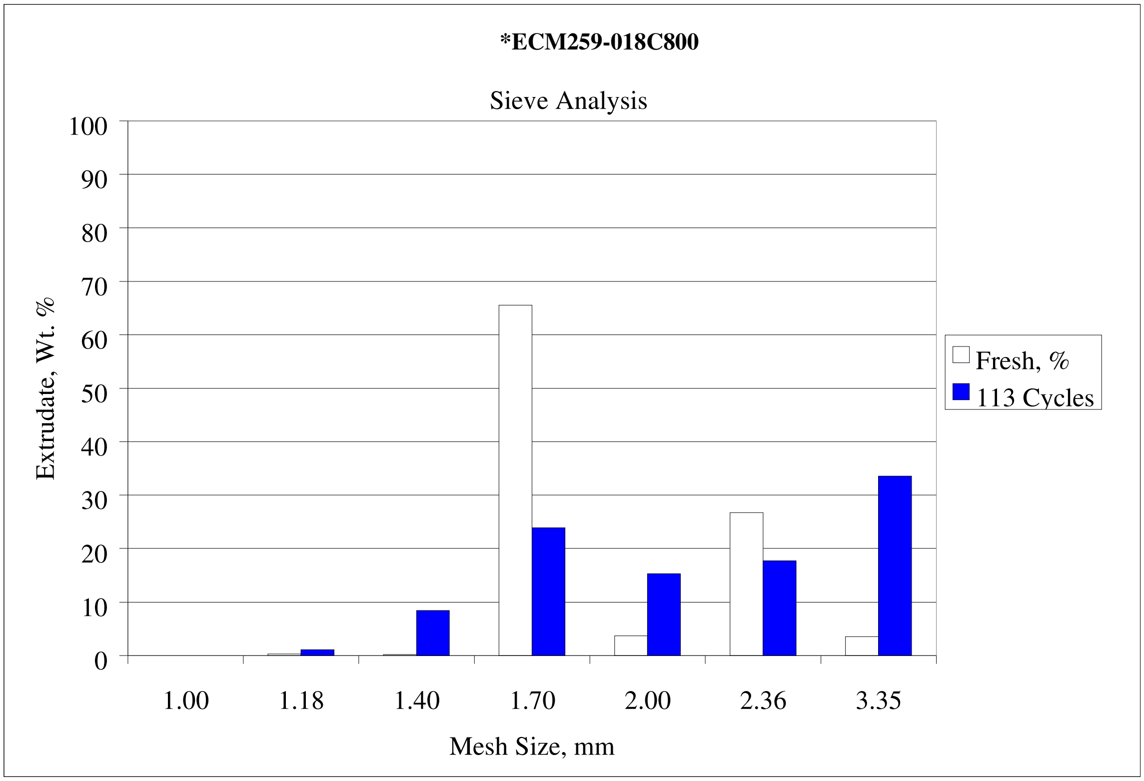

ECM259-002-2C
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
53 Cycles


ECM259-011C
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
77 Cycles


*ECM259-012C
Sieve Analysis
Extrudate, Wt. %
0
10
20
30
40
50
60
70
80
90
100
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
77 Cycles


*ECM259-013C
Sieve Analysis
Extrudate, Wt. %
100
90
80
70
60
50
40
30
20
10
0
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
113 Cycles


*ECM259-013C
Sieve Analysis
100
90
80
70
60
50
40
30
20
10
0
Extrudate, Wt. %
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
113 Cycles


*ECM259-018C800
Sieve Analysis
Extrudate, Wt. %
0
10
20
30
40
50
60
70
80
90
100
1.00
1.18
1.40
1.70
2.00
2.36
3.35
Mesh Size, mm
Fresh, %
113 Cycles

APPENDIX I

[illegible] Chevron Texaco Exchanger Design Cases
29-Aug-05
H:\[illegible]\Exchangers\[Exchanger Design Cases Rev. 5.xls]Sheet1

Exchanger	Case	Hotside Flow		Coldside Flow		Heat Cap Aver (btu/lb/F)		Hot In Temp		Hot Out Temp		Cold In Temp		Cold Out Temp		Hotside Duty		Coldside Duty		LMTD	Fouling U	HT Area	Thermal Exp Delta T (deg C)	Bypass On	Bypass			Mixed Temp		Full Flow Hotside Film	Full Flow Coldside Film	Full Flow Hotside Fouling	Full Flow Coldside Fouling	CC4C	U Calc
		(kg/hr)	(lb/hr)	(kg/hr)	(lb/hr)	Hotside	Coldside	°C	°F	°C	°F	°C	°F	°C	°F	(btu/hr)	(kW)	(btu/hr)	(kW)	°F		(ft2)			%	(kg/hr)	(lb/hr)	°C	°F						
HX1	Base Case	1674.24	3691.07	1615.62	3561.83	[illegible]	0.2544	710.6	1300.1	151.5	304.7	70.0	158.0	666.0	1230.1	971444	285	-971444	-285	116.05	7	1195	65												
HX1	Design: Hot in higher	1674.24	3691.07	1615.62	3561.83	[illegible]	[illegible]	800.0	1472.0	160.1	320.5	70.0	158.0	760.4	1370.2	1104682	324	-1104682	-324	131.95	7	1195	73												
HX1	Hot in lower	1674.24	3691.07	1615.62	3561.83	[illegible]	[illegible]	500.0	[illegible]	140.2	284.5	70.0	158.0	512.8	955.1	712647	209	-712647	-209	85.95	7	1195	45												
HX1	Cold in higher	1674.24	3691.07	1615.62	3561.83	[illegible]	[illegible]	[illegible]	[illegible]	301.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	704396	206	-704396	-206	84.14	7	1195	45												
HX1	Thermal Exp Design: Hot in higher, 300C Cold Outlet Temp (Process Cooling in Bypass)	1674.24	3691.07	485.40	1070.33	0.2600	0.2530	800.0	1472.0	601.3	1114.1	70.0	158.0	800.0	1472.0	365887	108	-365887	-108	60.42	8.12	1195	268	Coldside	80.05%	1130.13	2431.60	300.1	572.2	11.83	23.65			1.15	5.12
HX1	TV-4001 Design: Hot in higher, Cold in higher, 300C Cold Outlet Temp (Process Cooling in Bypass)	1674.24	3691.07	137.33	302.76	0.2600	0.2530	800.0	1472.0	757.6	1395.7	250.0	482.0	800.0	1472.0	76528	23	-76529	-22	19.39	2.89	977	254	Coldside	91.6%	1479.29	3259.08	289.8	571.6	11.83	23.65			1.15	2.86
HX1	Hot in higher and Cold in higher	1674.24	3691.07	1615.62	3561.83	0.2608	0.2530	800.0	1472.0	210.8	367.6	[illegible]	[illegible]	[illegible]	[illegible]	832066	244	-832066	-244	98.39	7	1195	50												
HX3	Base Case	42.32	93.30	326.60	720.09	1.1547	0.2470	350.0	662.0	95.0	203.0	70.0	158.0	222.8	433.1	49432	14.49	-49432	-14.49	106.06	7	62.47	75												
HX3	Design: Hot in higher	42.32	93.30	326.60	720.09	1.1818	0.2494	[illegible]	[illegible]	101.8	214.9	70.0	158.0	260.8	501.5	62112	18.20	-62112	-18.20	142.04	7	62.47	80												
HX3	Hot in lower	42.32	93.30	326.60	720.09	1.1400	0.2455	290.0	572.0	90.4	194.7	70.0	158.0	186.7	368.2	40459	11.86	-40459	-11.86	92.52	7	62.47	52												
HX3	Cold in higher	42.32	93.30	326.60	720.09	1.1619	0.2480	350.0	662.0	[illegible]	[illegible]	[illegible]	[illegible]	369.9	697.8	38981	11.42	-38981	-11.42	88.10	7	62.47	48												
HX3	Hot in and Cold in higher	42.32	93.30	326.60	720.09	1.1600	0.2507	420.0	788.0	[illegible]	[illegible]	[illegible]	[illegible]	342.7	648.6	30204	8.86	-30204	-8.86	68.36	7	62.47	46												
HX2	Base Case	42.32	93.30	326.60	720.09	1.2026	0.2539	600.0	1112.0	246.3	475.1	202.5	433.1	439.2	822.5	71117	20.84	-71117	-20.84	131.36	7	77.36	33												
HX2	HX3 Hot in higher	42.32	93.30	326.60	720.09	1.2252	0.2530	600.0	1112.0	260.0	482.0	260.8	501.5	455.0	850.9	64100	18.79	-64100	-18.79	118.30	7	77.36	34												
HX2	HX3 Hot in lower	42.32	93.30	326.60	720.09	1.2004	0.2511	600.0	1112.0	222.5	432.5	186.7	368.2	427.6	802.3	76107	22.30	-76107	-22.30	140.88	7	77.36	99												
HX2	HX3 Cold in higher	42.32	93.30	326.60	720.09	1.2056	0.2530	600.0	1112.0	[illegible]	[illegible]	[illegible]	[illegible]	501.6	934.9	43496	12.75	-43496	-12.75	80.30	7	77.36	97												
HX2	Design: HX2 Hot in higher, Coldest HX3 Cold Outlet	42.32	93.30	326.60	720.09	1.2267	0.2567	800.0	1472.0	238.2	460.8	185.7	364.3	544.9	1012.9	115636	33.89	-115636	-33.89	213.57	7	77.36	149												
HX2	HX2 Hot in higher, Coldest HX3 Cold Outlet, 300C Hot outlet (Coldside Bypass)	42.32	93.30	215.43	474.93	1.2267	0.2507	800.0	1472.0	260.0	571.7	185.7	364.3	670.4	1238.7	102952	30.17	-102952	-30.17	209.54	6.33	77.36	117	Coldside	34.03%	112.47	250.10	312.2	594.0	11.83	23.65	0.002	0.001	1.15	6.32
HX2	TV-10108 Design: HX2 Hot in colder, Coldest HX3 Cold Outlet, 300C Hot outlet (Coldside Bypass)	42.32	93.30	165.27	364.36	1.2267	0.2608	600.0	1112.0	300.2	572.2	185.7	364.3	587.1	1062.8	61772	18.10	-61772	-18.10	113.47	7.16	77.36	60	Coldside	49.75%	163.63	360.73	368.8	731.8	13.73	53.63			1.15	7.16
HX2	TV-10109 Turndown: HX2 Hot in hotter, Coldest HX3 Cold Outlet, 250C Hot outlet (Coldside Bypass)	42.32	93.30	266.00	[illegible]	1.2267	0.2538	800.0	1472.0	250.0	482.0	185.7	364.3	618.6	1146.0	113310	33.21	-113310	-33.21	189.47	7.73	77.36	118	Coldside	19.10%	62.63	138.49	542.5	1008.5	13.73	53.63			1.15	7.73
HX2	TV-10109 Turndown: HX2 Hot in hotter, 260.8C HX3 Cold Outlet, 300C Hot outlet (Coldside Bypass)	42.32	93.30	299.73	660.80	1.2267	0.2608	800.0	1472.0	300.0	571.9	260.8	501.5	612.9	1135.2	103014	30.19	-103014	-30.19	173.24	7.82	77.36	113	Coldside	11.69%	38.15	84.11	574.8	1066.1	13.73	53.63			1.15	7.42
HX2	HX: Hot in higher, Hottest HX3 Cold Outlet	42.32	93.30	326.60	720.09	1.2330	0.2563	800.0	1472.0	[illegible]	[illegible]	[illegible]	[illegible]	617.3	1142.6	82832	24.28	-82832	-24.28	162.96	7	77.36	107												
Preheater 1 (HX4)	Design: HX2 Hottest Outlet, Water Hotter Inlet	42.32	93.30	72.64	160.14	1.1775	1.0000	[illegible]	[illegible]	250.0	482.0	43.3	110.0	135.5	275.9	26725	7.83	-26725	-7.83	409.02	10	6.33	228												
Preheater 1 (HX4)	Thermal Exp Design: HX2 Hottest Outlet, Water Coldest Inlet	42.32	93.30	72.64	160.14	1.1775	1.0000	[illegible]	[illegible]	250.0	482.0	15.5	60.0	150.7	318.9	26725	7.83	-26725	-7.83	489.17	10	5.70	261												

	ZETON EXCHANGER DATA SHEET (HEXSPEC2.XLS SEP25/98)			SHEET	1	OF 2
REV NO	DESCRIPTION	DATE	DATA SHEET NO:		REV NO:	3
0	ISSUED TO CLIENT FOR APPROVAL	05-Jul-05	JOB NO:	757-20	DATE:	25-Aug-05
1	ISSUED FOR RFQ	07-Jul-05	DIRECTORY:			
2	LINE 14, 16, 53, 64	24-Aug-05	FILE:	H:\757-20\Exchangers\HX1 Specification Rev 3.XLS\SPECIFICATION		
3	SWITCHED SHELLSIDE/TUBESIDE. NOTE 10	25-Aug-05	TAG NO.	HX-1		
1	SERVICE OF UNIT:					
2	SIZE:	***	TYPE:	***	NUM OF UNITS:	1
3	MANUFACTURER:					
4	GROSS SURFACE AREA/UNIT:	FT2	***		CONNECTED IN:	
	PERFORMANCE OF ONE UNIT					
			SHELL SIDE		TUBE SIDE	
5	FLUID CIRCULATED:	VOLUME %	1.40% OF H2O, 2.78% OF CO2, 18.90% OF O2 AND 76.81% OF N2		21% OF O2 AND 79% OF N2	
6	TOTAL FLUID ENTERING:	LB/HR	3691.02		3561.8	
7			IN	OUT	IN	OUT
8	LIQUID:	LB/HR				
9	VAPOUR:	LB/HR	3691.02	3691.02	3561.8	3561.8
10	NON-CONDENSABLES:	LB/HR				
11						
12	TEMPERATURE:	DEG F	1472.0	325.3	158.0	1370.2
	TEMPERATURE:	DEG °C	800.0	162.9	70.0	743.4
13	DEW (BUBBLE) POINT:	DEG F				
14	OPERATING PRESSURE:	PSIG	8.7	4.6	36.9	32.6
15	FLUID VAPOURIZED OR CONDENSED:	LB/HR				
16	MOL WEIGHT - VAPOURS:		29.067		28.85	
17	MOL WEIGHT - NON CONDENSABLES:					
18	DENSITY - LIQUID / VAPOUR:	LB/FT3	0.0328 (***)	0.0666 (***)	0.2246 (***)	0.0595 (***)
19	VISCOSITY - LIQUID / VAPOUR:	CP	0.044 (***)	0.0241 (***)	0.0205 (***)	0.0436 (***)
20	SPECIFIC HEAT - LIQUID / VAPOUR:	BTU/LB/F	0.275 (***)	0.247 (***)	0.242 (***)	0.276 (***)
21	THERMAL CONDUCTIVITY:	BTU/HR-FT-F	0.0391 (***)	0.0148 (***)	0.0166 (***)	0.0192 (***)
22	LATENT HEAT:	BTU/LB				
23						
24	VELOCITY:	FT/SEC	***		***	
25	PRESSURE DROP - ALLOW / CALC:	PSI	4.1 / ***		4.3 / ***	
26	FOULING RESISTANCE:	FT2-HR-F/BTU	0.002		0.001	
27						
28	HEAT EXCHANGED:	BTU/HR	1105075	LMTD CORRECTED	DEG F	***
29	EFF SURFACE AREA / UNIT	FT2	*** (NOTE 1)			
			REQUIRED	CLEAN	DIRTY	
30	TRANSFER RATE	BTU/FT2-HR-F	***	***	***	
	CONSTRUCTION					
			SHELL SIDE		TUBE SIDE	
31	DESIGN / TEST PRESSURE:	PSIG	50 PSIG / PER CODE		50 PSIG / PER CODE	
32	DESIGN TEMPERATURE:	DEG F	1500		1500	
33	NO PASSES PER SHELL:		***		1	
34	CORROSION ALLOWANCE:	INCH	1/16" ON OD (EXPOSED TO ATMOSPHERE), NO CORROSION ALLOWANCE ON TUBES		1/16" ON OD (EXPOSED TO ATMOSPHERE)	
35	MAT'L OF CONSTRUCTION:		304H WETTED PARTS		304H WETTED PARTS	
36	FINISH:		N/A		N/A	
37	CONNECTIONS:	INLET:	4" 600# ANSI		4" 600# ANSI	
38		OUTLET:	2" 600# ANSI		4" 600# ANSI	
39	TUBES - NUMBER:	***	OD:	***	WALL (INCH):	***
40			LENGTH:	***	PITCH:	***
41	SHELL - OD:	INCH	***	ID	INCH	***
42	TUBE TO TUBESHEET JOINT:	STRENGTH WELDED, REMOVE ALL CONTAMINATION OILS ETC FROM THE TUBE HOLE AND THE TUBE OD (NOTE 4)		TUBESHEET (FLOAT/STATIONARY)		***
43	CHANNEL OR BONNET	***		CHANNEL COVER	***	
44	SHELL COVER	***		FL HEAD COVER	***	
45	BAFFLES (CROSS) NUMBER:	***	TYPE:	***	SPACING:	***
46		% CUT	(DIA/AREA)	***		
47	BAFFLES (LONGITUDINAL) NUMBER:	N/A	TYPE:	N/A		
48	TUBE SUPPORTS:	***		GASKETS:	***	
49	EXPANSION JOINT:	AS REQ'D		INSUL SUPPORT:	N/A	
50	CODE REQ'D:	ASME VIII		REGISTRATION:	"U" STAMP, NATIONAL BOARD REGISTERED	
51	TEMA CLASS:	N/A		TEMA TYPE:	***	
52	MOUNTING BRACKETS:	YES		LIFTING LUGS:	YES	
53	WEIGHT - TOTAL PER SHELL:	***	BUNDLE:	***	FULL OF WATER:	***
54	NOTE: INDICATE AFTER EACH PART WHETHER OR NOT IT IS STRESS RELIEVED (SR) AND/OR RADIOGRAPHED (XR)					
	NOTES					
55	*** INDICATES INFORMATION THAT IS TO BE SUPPLIED OR CONFIRMED BY VENDOR.					
56	1. DESIGN WITH 10% EXCESS AREA ABOVE DIRTY SURFACE AREA.					
57	2. THE ABOVE CONDITIONS IS ALSO THE WORST THERMAL EXPANSION CASE.					
58	3. DESIGN FOR PRELIMINARY NOZZLE LOADS (AT MAX DESIGN TEMPERATURE) AS GIVEN ON PAGE2					
59	4. TUBE TO TUBESHEET JOINT MUST BE LEAK TESTED WITH HELIUM AND SOAP BUBBLE AT 50 PSIG					
60	5. NO PWHT REQUIRED					
61	6. EXCHANGER WILL EXPERIENCE 10,000 THERMAL CYCLES OVER IT'S LIFE TIME					
62	7. SEE ATTACHED FILES (PVM-DG-4766-B.PDF AND EXH-DG-4764.PDF)					
63	8. THERMAL EXPANSION DESIGN BASED UPON 91.5% BYPASS OF COLD AIR: HOT INLET/OUTLET: 1472F/1114F, COLD INLET/OUTLET: 70F/1472F					
64	9. IF MORE THAN ONE UNIT IS REQUIRED, PRESSURE DROP SHOULD INCLUDE INTERCONNECTING PIPING.					
65	10. SHELLSIDE PRESSURE CAN NEVER BE GREATER THAN TUBESIDE PRESSURE BECAUSE THE SHELLSIDE IS DOWNSTREAM.					

ZETON EXCHANGER DATA SHEET (HEXSPEC2.XLS SEP25/98)			SHEET	1	OF 2
REV NO	DESCRIPTION	DATE	DATA SHEET NO:	REV NO	4
1	ISSUED FOR RFQ		JOB NO: 757-20	DATE:	25-Aug-05
2	CHANGED H2 TO N2 ON SHELLSIDE	04-Aug-05	DIRECTORY:		
3	LINE 14,18,25,37,38, DELETED NOTE 2	24-Aug-05	FILE:	H:\757-20\Exchangers\[HX2 Specification Rev 4.XLS]SPECIFICATION	
4	SWITCHED SHELLSIDE/TUBESIDE, LINE 14, 18, 32, 37, NOTE 8, NOZZLE LOADS	25-Aug-05	TAG NO:	HX-2	

1	SERVICE OF UNIT:					
2	SIZE:	***	TYPE:	***	NUM OF UNITS:	1
3	MANUFACTURER:					
4	GROSS SURFACE AREA/UNIT:	FT2	***		CONNECTED IN:	
	PERFORMANCE OF ONE UNIT					
			SHELL SIDE		TUBE SIDE	
5	FLUID CIRCULATED	VOLUME %	73.45% OF H2, 24.08% OF H2O, 0.39% OF CO2, 0.39% OF CO AND 1.74% OF CH4		21% OF O2 AND 79% OF N2	
6	TOTAL FLUID ENTERING:	LB/HR	93.29		725.08	
7			IN	OUT	IN	OUT
8	LIQUID:	LB/HR				
9	VAPOUR:	LB/HR	93.29	93.29	725.08	725.08
10	NON-CONDENSABLES:	LB/HR				
11						
12	TEMPERATURE:	DEG F	1472.0	460.6	368.3	1012.8
	TEMPERATURE:	DEG °C	800.0	238.2	186.7	544.9
13	DEW (BUBBLE) POINT:	DEG F				
14	OPERATING PRESSURE:	PSIG	12.1	10.1	20.5	18.4
15	FLUID VAPOURIZED OR CONDENSED:	LB/HR				
16	MOL WEIGHT - VAPOURS:		6.65		28.85	
17	MOL WEIGHT - NON CONDENSABLES:					
18	DENSITY - LIQUID / VAPOUR:	LB/FT3	0.0062 (***)	0.0160 (***)	0.1131 (***)	0.0604 (***)
19	VISCOSITY - LIQUID / VAPOUR:	CP	0.0351 (***)	0.0176 (***)	0.0257 (***)	0.0372 (***)
20	SPECIFIC HEAT - LIQUID / VAPOUR:	BTU/LB/F	1.283 (***)	1.166 (***)	0.246 (***)	0.261 (***)
21	THERMAL CONDUCTIVITY:	BTU/HR-FT-F	0.1924 (***)	0.1047 (***)	0.0213 (***)	0.0175 (***)
22	LATENT HEAT:	BTU/LB				
23						
24	VELOCITY:	FT/SEC	***		***	
25	PRESSURE DROP - ALLOW / CALC:	PSI	2 / ***		2.1 / ***	
26	FOULING RESISTANCE:	FT2-HR-F/BTU	0.002		0.001	
27						
28	HEAT EXCHANGED:	BTU/HR	115636	LMTD CORRECTED	DEG F	***
29	EFF SURFACE AREA / UNIT	FT2	*** (NOTE 1)			
			REQUIRED	CLEAN	DIRTY	
30	TRANSFER RATE	BTU/FT2-HR-F	***	***	***	
	CONSTRUCTION					
			SHELL SIDE		TUBE SIDE	
31	DESIGN / TEST PRESSURE:	PSIG	50 PSIG / PER CODE		50 PSIG / PER CODE	
32	DESIGN TEMPERATURE:	DEG F	1500		1300	
33	NO PASSES PER SHELL:		***		1	
34	CORROSION ALLOWANCE:	INCH	(SED TO ATMOSPHERE), NO CORROSION ALLO		1/16" ON OD (EXPOSED TO ATMOSPHERE)	
35	MAT'L OF CONSTRUCTION:		304H WETTED PARTS		304H WETTED PARTS	
36	FINISH:		N/A		N/A	
37	CONNECTIONS:	INLET:	2" 600# ANSI		2" 300# ANSI	
38		OUTLET:	2" 600# ANSI		2" 300# ANSI	
39	TUBES - NUMBER:	***	OD:	***	WALL (INCH):	***
40			LENGTH:	***	PITCH:	***
41	SHELL - OD:	INCH	***	10	INCH	***
42	TUBE TO TUBESHEET JOINT:	STRENGTH WELDED; REMOVE ALL CONTAMINATION OILS ETC FROM THE TUBE HOLE AND THE TUBE OD (NOTE 4)		TUBESHEET (FLOAT/STATIONARY)		***
43	CHANNEL OR BONNET	***		CHANNEL COVER	***	
44	SHELL COVER	***		FL HEAD COVER	***	
45	BAFFLES (CROSS) NUMBER:	***	TYPE:	***	SPACING:	***
46		% CUT	(DIA/AREA):	***		
47	BAFFLES (LONGITUDINAL) NUMBER:	N/A	TYPE:	N/A		
48	TUBE SUPPORTS:	***		GASKETS:	***	
49	EXPANSION JOINT:	AS REQ'D		INSUL SUPPORT:	N/A	
50	CODE REQ'D:	ASME VIII		REGISTRATION:	"U" STAMP, NATIONAL BOARD REGISTERED	
51	TEMA CLASS:	N/A		TEMA TYPE:	***	
52	MOUNTING BRACKETS:	YES		LIFTING LUGS:	YES	
53	WEIGHT - TOTAL PER SHELL:	***	BUNDLE:	***	FULL OF WATER:	***
54	NOTE: INDICATE AFTER EACH PART WHETHER OR NOT IT IS STRESS RELIEVED (SR) AND/OR RADIOGRAPHED (XR)					
	NOTES					
55	*** INDICATES INFORMATION THAT IS TO BE SUPPLIED OR CONFIRMED BY VENDOR.					
56	1. DESIGN WITH 10% EXCESS AREA ABOVE DIRTY SURFACE AREA.					
57						
58	3. DESIGN FOR PRELIMINARY NOZZLE LOADS (AT MAX DESIGN TEMPERATURE) AS GIVEN ON PAGE2					
59	4. TUBE TO TUBESHEET JOINT MUST BE LEAK TESTED WITH HELIUM AND SOAP BUBBLE AT 50 PSIG.					
60	5. NO PWHT REQUIRED					
61	6. EXCHANGER WILL EXPERIENCE 10,000 THERMAL CYCLES OVER IT'S LIFE TIME					
62	7. SEE ATTACHED FILES (PVW-EQ-4740-0.PDF AND EXH-EQ-4704.PDF)					
63	8. A DIFFERENTIAL PRESSURE SWITCH WILL BE ADDED TO SHUTOFF FLOW IF THE SHELLSIDE PRESSURE EXCEEDS THE TUBESIDE PRESSURE.					

ZETON EXCHANGER DATA SHEET (HEXSPEC2.XLS SEP25/98)			SHEET		1	OF 2
REV NO	DESCRIPTION	DATE	DATA SHEET NO:		REV NO:	3
0	ISSUED TO CLIENT FOR APPROVAL	05-Jul-05	JOB NO:	757-20	DATE:	25-Aug-05
1	ISSUED FOR RFQ		DIRECTORY:			
2	LINES 14, 18	24-Aug-05	FILE:	H:\757-20\Exchangers\[HX3 Specification Rev 2.XLS]SPECIFICATION		
3	LINES 14, 18, 32, 37, 38, NOZZLE LOADS	25-Aug-05	TAG NO:	HX-3		
1	SERVICE OF UNIT:					
2	SIZE:	***	TYPE:	***	NUM OF UNITS:	1
3	MANUFACTURER:					
4	GROSS SURFACE AREA/UNIT:	FT2	***		CONNECTED IN:	
	PERFORMANCE OF ONE UNIT					
			SHELL SIDE		TUBE SIDE	
5	FLUID CIRCULATED:	VOLUME %	21% OF O2 AND 79% OF N2		71.94% OF H2, 25.54% OF H2O, AND 2.52% OF CH4	
6	TOTAL FLUID ENTERING:	LB/HR	725.08		93.3	
7			IN	OUT	IN	OUT
8	LIQUID:	LB/HR				
9	VAPOUR:	LB/HR	725.08	725.08	93.3	93.3
10	NON-CONDENSABLES:	LB/HR				
11						
12	TEMPERATURE:	DEG F	158.0	591.5	788.0	214.9
	TEMPERATURE:	DEG °C	70.0	285.8	420.0	101.6
13	DEW (BUBBLE) POINT:	DEG F				
14	OPERATING PRESSURE:	PSIG	23.3	21.3	5.5	3.5
15	FLUID VAPOURIZED OR CONDENSED:	LB/HR				
16	MOL WEIGHT - VAPOURS:		28.85		6.454	
17	MOL WEIGHT - NON CONDENSABLES:					
18	DENSITY - LIQUID / VAPOUR:	LB/FT3	0.1054 (***)	0.1007 (***)	0.0097 (***)	0.0162 (***)
19	VISCOSITY - LIQUID / VAPOUR:	CP	0.0205 (***)	0.0282 (***)	0.0224 (***)	0.0125 (***)
20	SPECIFIC HEAT - LIQUID / VAPOUR:	BTU/LB F	0.256 (***)	0.243 (***)	1.191 (***)	1.132 (***)
21	THERMAL CONDUCTIVITY:	BTU/HR-FT-F	0.0166 (***)	0.0185 (***)	0.1345 (***)	0.0757 (***)
22	LATENT HEAT:	BTU/LB				
23						
24	VELOCITY:	FT/SEC	***		***	
25	PRESSURE DROP - ALLOW / CALC:	PSI	2 / ***		2 / ***	
26	FOULING RESISTANCE:	FT2-HR-F/BTU	0.001		0.002	
27						
28	HEAT EXCHANGED:	BTU/HR	82114	LMTD CORRECTED	DEG F	***
29	EFF SURFACE AREA / UNIT:	FT2	*** (NOTE 1)			
			REQUIRED	CLEAN	DIRTY	
30	TRANSFER RATE:	BTU/FT2 HR F	***	***	***	
	CONSTRUCTION					
			SHELL SIDE		TUBE SIDE	
31	DESIGN / TEST PRESSURE:	PSIG	50 PSIG / PER CODE		50 PSIG / PER CODE	
32	DESIGN TEMPERATURE:	DEG F	700		900	
33	NO PASSES PER SHELL:		1		***	
34	CORROSION ALLOWANCE:	INCH	1/16" ON OD (EXPOSED TO ATMOSPHERE)		1/16" ON OD (EXPOSED TO ATMOSPHERE), NO CORROSION ALLOWANCE ON TUBES	
35	MAT'L OF CONSTRUCTION:		304/304L DUAL GRADE WETTED PARTS		304/304L DUAL GRADE WETTED PARTS	
36	FINISH:		N/A		N/A	
37	CONNECTIONS:	INLET:	1.5" 150# ANSI		2" 150# ANSI	
38		OUTLET:	1.5" 150# ANSI		1.5" 150# ANSI	
39	TUBES - NUMBER:	***	OD:	***	WALL (INCH):	***
40			LENGTH:	***	PITCH:	***
41	SHELL - OD:	INCH	***	ID	INCH	***
42	TUBE TO TUBESHEET JOINT:	STRENGTH WELDED, REMOVE ALL CONTAMINATION OILS ETC FROM THE TUBE HOLE AND THE TUBE OD (NOTE 4)		TUBESHEET (FLOAT/STATIONARY)		***
43	CHANNEL OR BONNET:	***		CHANNEL COVER:	***	
44	SHELL COVER:	***		FL HEAD COVER:	***	
45	BAFFLES (CROSS) NUMBER:	***	TYPE:	***	SPACING:	***
46		% CUT	(DIA/AREA):	***		
47	BAFFLES (LONGITUDINAL) NUMBER:	N/A	TYPE:	N/A		
48	TUBE SUPPORTS:	***		GASKETS:	***	
49	EXPANSION JOINT:	AS REQ'D		INSUL SUPPORT:	N/A	
50	CODE REQ'D:	ASME VIII		REGISTRATION:	"U" STAMP, NATIONAL BOARD REGISTERED	
51	TEMA CLASS:	N/A		TEMA TYPE:	***	
52	MOUNTING BRACKETS:	YES		LIFTING LUGS:	YES	
53	WEIGHT - TOTAL PER SHELL:	***	BUNDLE:	***	FULL OF WATER:	***
54	NOTE: INDICATE AFTER EACH PART WHETHER OR NOT IT IS STRESS RELIEVED (SR) AND/OR RADIOGRAPHED (XR)					
	NOTES					
55	*** INDICATES INFORMATION THAT IS TO BE SUPPLIED OR CONFIRMED BY VENDOR.					
56	1. DESIGN WITH 10% EXCESS AREA ABOVE DIRTY SURFACE AREA					
57	2. THE ABOVE CONDITIONS IS ALSO THE WORST THERMAL EXPANSION CASE.					
58	3. DESIGN FOR PRELIMINARY NOZZLE LOADS (AT MAX DESIGN TEMPERATURE) AS GIVEN ON PAGE2					
59	4. TUBE TO TUBESHEET JOINT MUST BE LEAK TESTED WITH HELIUM AND SOAP BUBBLE AT 50 PSIG.					
60	5. NO PWHT REQUIRED					
61	6. EXCHANGER WILL EXPERIENCE 10,000 THERMAL CYCLES OVER IT'S LIFE TIME					
62	7. SEE ATTACHED FILES (PVM-EG-A748-R.PDF AND EXH-EG-A784.PDF)					

ZETON EXCHANGER DATA SHEET (HEXSPEC2.XLS SEP25/98)			SHEET		1	OF 2
REV NO	DESCRIPTION	DATE	DATA SHEET NO:		REV NO:	2
0	ISSUED TO CLIENT FOR APPROVAL	05-Jul-05	JOB NO:	757-20	DATE:	25-Aug-05
1	SEE PURPLE	24-Aug-05	DIRECTORY:			
2	SEE PURPLE	25-Aug-05	FILE:	H:\757-20\Exchangers\[HX4 Specification Rev 2.XLS]SPECIFICATION		
			TAG NO:	HX-4		
1	SERVICE OF UNIT:					
2	SIZE:	***	TYPE:	***	NUM OF UNITS:	1
3	MANUFACTURER:					
4	GROSS SURFACE AREA/UNIT:	FT2	***		CONNECTED IN:	
	PERFORMANCE OF ONE UNIT					
			SHELL SIDE		TUBE SIDE	
5	FLUID CIRCULATED:	VOLUME %	DEMINERALIZED NON-DEAERATED WATER		73.45% OF H2, 24.06% OF H2O, 0.35% OF CO2, 0.39% OF CO AND 1.74% OF CH4	
6	TOTAL FLUID ENTERING:	LB/HR	72.64		93.29	
7			IN	OUT	IN	OUT
8	LIQUID:	LB/HR				
9	VAPOUR:	LB/HR	72.64	72.64	93.29	93.29
10	NON-CONDENSABLES:	LB/HR				
11						
12	TEMPERATURE:	DEG F	116.0	277.5	725.3	482.0
	TEMPERATURE:	DEG °C	43.3	136.4	385.2	250.0
13	DEW (BUBBLE) POINT:	DEG F	280.6	277.9		
14	OPERATING PRESSURE:	PSIG	27.5	25.0	10	5
15	FLUID VAPOURIZED OR CONDENSED:	LB/HR	N/A			
16	MOL WEIGHT - VAPOURS:				6.35	
17	MOL WEIGHT - NON CONDENSABLES:					
18	DENSITY - LIQUID / VAPOUR:	LB/FT3	61.8 (***)	58.1 (***)	0.0134 (***)	[illegible]
19	VISCOSITY - LIQUID / VAPOUR:	CP	0.616 (***)	0.208 (***)	0.0214 (***)	0.0174 (***)
20	SPECIFIC HEAT - LIQUID / VAPOUR:	BTU/LB/F	0.997 (***)	1.02 (***)	1.195 (***)	1.170 (***)
21	THERMAL CONDUCTIVITY:	BTU/HR-FT-F	0.369 (***)	0.395 (***)	0.1313 (***)	0.0920 (***)
22	LATENT HEAT:	BTU/LB				
23						
24	VELOCITY:	FT/SEC	***		***	
25	PRESSURE DROP - ALLOW / CALC:	PSI	2 / ***		2 / ***	
26	FOULING RESISTANCE:	FT2-HR-F/BTU	0.001		0.002	
27						
28	HEAT EXCHANGED	BTU/HR	[illegible]	LMTD CORRECTED	DEG F	***
29	EFF SURFACE AREA / UNIT	FT2	*** (NOTE 1)			
			REQUIRED	CLEAN	DIRTY	
30	TRANSFER RATE	BTU/FT2-HR-F	***	***	***	
	CONSTRUCTION					
			SHELL SIDE		TUBE SIDE	
31	DESIGN / TEST PRESSURE:	PSIG	70 PSIG / PER CODE		50 PSIG / PER CODE	
32	DESIGN TEMPERATURE:	DEG F	350		900	
33	NO PASSES PER SHELL:		1		***	
34	CORROSION ALLOWANCE:	INCH	0		0	
35	MAT'L OF CONSTRUCTION:		304/304L DUAL GRADE WETTED PARTS		304/304L DUAL GRADE WETTED PARTS	
36	FINISH:		N/A		N/A	
37	CONNECTIONS:	INLET:	1/2" FNPT		1.5" 150# ANSI	
38		OUTLET:	1/2" FNPT		2" 150# ANSI	
39	TUBES - NUMBER:	***	OD:	***	WALL (INCH):	***
40			LENGTH:	***	PITCH:	***
41	SHELL - OD:	INCH	***	10	INCH	***
42	TUBE TO TUBESHEET JOINT:	*** (NOTE 4)		TUBESHEET (FLOAT/STATIONARY)		***
43	CHANNEL OR BONNET	***		CHANNEL COVER	***	
44	SHELL COVER	***		FL HEAD COVER	***	
45	BAFFLES (CROSS) NUMBER:	***	TYPE:	***	SPACING:	***
46		% CUT	(DIA/AREA):	***		
47	BAFFLES (LONGITUDINAL) NUMBER:	N/A	TYPE:	N/A		
48	TUBE SUPPORTS:	***		GASKETS:	***	
49	EXPANSION JOINT:	AS REQ'D		INSUL SUPPORT:	N/A	
50	CODE REQ'D:	ASME VIII		REGISTRATION:	"U" STAMP, NATIONAL BOARD REGISTERED	
51	TEMA CLASS:	N/A		TEMA TYPE:	***	
52	MOUNTING BRACKETS:	YES		LIFTING LUGS:	YES	
53	WEIGHT - TOTAL PER SHELL:	***	BUNDLE:	***	FULL OF WATER:	***
54	NOTE: INDICATE AFTER EACH PART WHETHER OR NOT IT IS STRESS RELIEVED (SR) AND/OR RADIOGRAPHED (XR)					
	NOTES					
55	*** INDICATES INFORMATION THAT IS TO BE SUPPLIED OR CONFIRMED BY VENDOR.					
56	1. DESIGN WITH 10% EXCESS AREA ABOVE DIRTY SURFACE AREA					
57	2. THERMAL EXPANSION DESIGN: 725.3F TUBE IN, 482F TUBE OUT, 50F SHELL IN, 214.5F SHELL OUT					
58	3. DESIGN FOR PRELIMINARY NOZZLE LOADS (AT MAX DESIGN TEMPERATURE) AS GIVEN ON PAGE 2					
59	4. TUBE TO TUBESHEET JOINT MUST BE LEAK TESTED WITH HELIUM AND SOAP BUBBLE AT 50 PSIG.					
60	5. SEE ATTACHED FILES (PVM-EG-4746-B.PDF AND EXH-EG-4764.PDF)					
61						
62						

APPENDIX J

ZETON VESSEL SPECIFICATION SHEET (VESSLSPS.XLS, REV. 6, OCT2099)

TAG/ITEM: R-1 (REACTOR) CLIENT: PROJECT #: 751-20 DATE: 28-Aug-05 PAGE 1 OF 2 REV. NO. A

DESIGN CRITERIA	PRESSURE	TEMPERATURE
DESIGN (MAWP) SHELL	50 PSIG	650 DEG F
JACKET		
OPERATING SHELL	45 PSIG MAX	450 DEG F MAX
JACKET		
MINIMUM SHELL	FULL VACUUM	70 DEG F
JACKET		

CAPACITY:		DESIGN CODES:	ASME VIII, DIV 1
L/D RATIO:		MATERIAL (SHELL):	CS (SA285-C OR SA516-70)
SHELL DIAMETER:	30" OD	MATERIAL (JACKET):	
SHELL LENGTH:	12'6" TAN TO FLANGE	MATERIAL (INTERNAL COIL):	
BAFFLES REQ'D:	INTERNAL ANCHORS FOR REFRACTORY WELDED TO SHELL, ID QUANTITY WILL BE SUPPLIED	INT WELD FINISH (SHELL):	FLUX, SPLATTER AND STAIN REMOVED (WHERE POSSIBLE)
JACKET DIAMETER:		INT WELD FINISH (JACKET):	
JACKET LENGTH:		EXT WELD FINISH (SHELL):	FLUX, SPLATTER AND STAIN REMOVED (WHERE POSSIBLE)
INTERNAL COIL:		EXT WELD FINISH (JACKET):	
REACTOR SUPPORT:	THREE GUSSETTED SUPPORTS	INTERNAL FINISH (SHELL):	STD MILL
CORR ALLOW. SHELL:	1/8"	INTERNAL FINISH (JACKET):	
CORR ALLOW. JACKET:		EXTERNAL FINISH (SHELL):	STD MILL
PRODUCT (STATE):	GAS (H2, AIR, CO, CO2, CH4)	EXTERNAL FINISH (JACKET):	
PRODUCT VISCOSITY:		INSULATION:	INTERNAL REFRACTORY (BY OTHERS)
PRODUCT DENSITY:	13000 LBS OF REFRACTORY AND CATALYST	LIFTING LUGS:	TWO

CLOSURE DESIGN	TOP HEAD	BOTTOM HEAD
CLOSURE TYPE	150# B16.47 FLANGE	2:1 SEMI-ELLIP HEAD
CLOSURE MATERIAL	CS	SA285-C OR SA516-70
GASKET/CLOSURE SIZE	30"	30" OD
GASKET MATERIAL	SEE PAGE 2	N/A
QUANTITY	3 (1 INSTALLED, 2 SPARES)	1

TESTS / CALCULATIONS		NOTES:
HYDROSTATIC	PER CODE	
RADIOGRAPH	SPOT (GREATER OF 2 SPOTS MIN PER WELDER OR CODE REQUIREMENT)	
DYE PENETRANT	PER CODE, LIFTING AND SUPPORT LUGS	
CODE STAMP	"U" REGISTERED, NATIONAL BOARD REGISTERED	
SPECIAL CALCS		

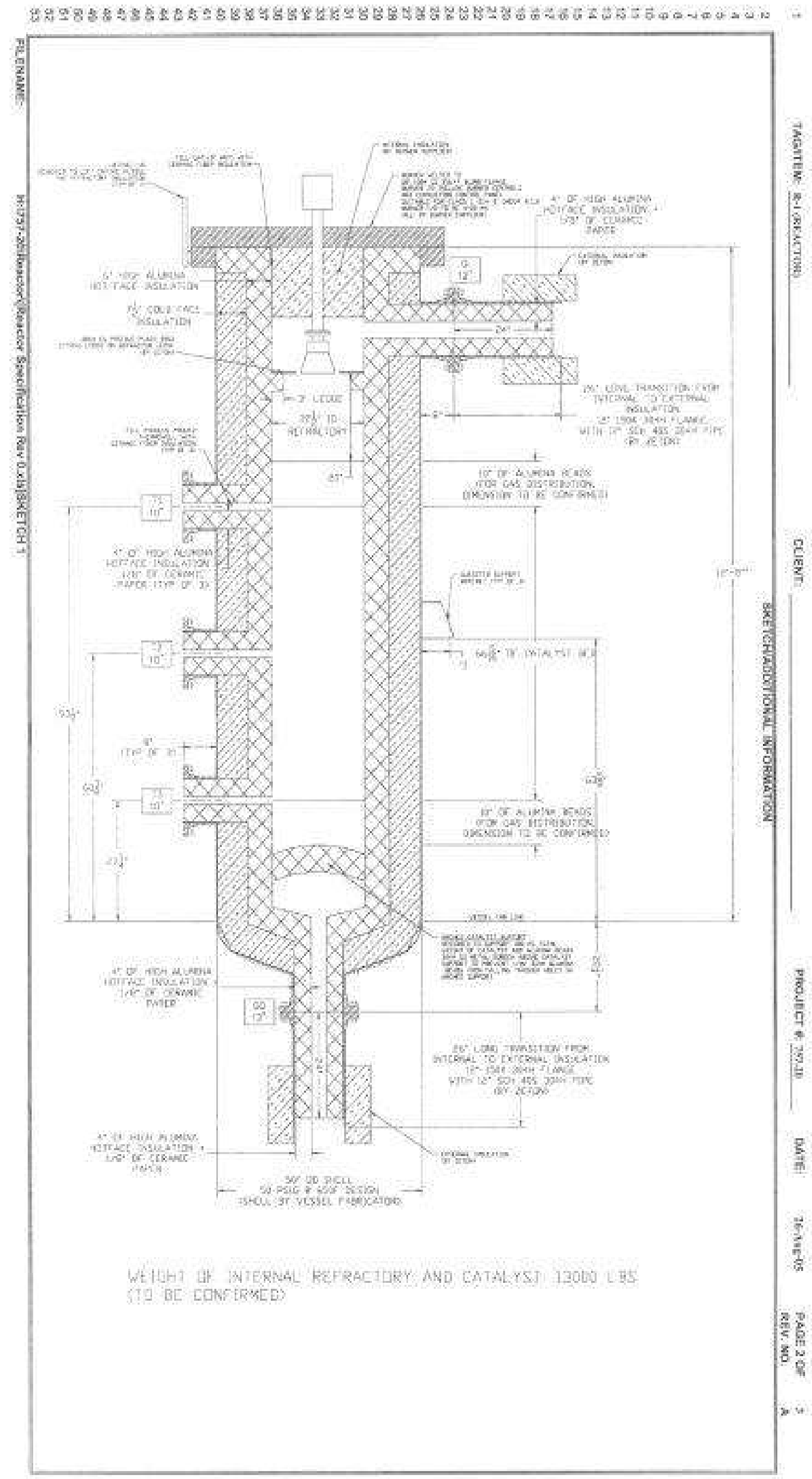
PORT CONNECTIONS FOR VESSEL

LOCATION	SIZE	NO.	DESCRIPTION	LENGTH
0	12" 150# RFWN	1	GAS INLET	6" OD TO RF
180	12" 150# RFWN	1	GAS OUTLET	6" OD TO RF
T1, T2, T3	1" 150# RFWN	3	THERMOWELLS	20.25" TAN TO RF

REVISED LINE NO. / DESCRIPTION	BY	DATE	REV. NO.	APPR.
ISSUED FOR FIRM PRICE QUOTATION	TF	28-Aug-05	A	EW

SKETCH/ADDITIONAL INFORMATION

H:\751\20\Reactor\[Reactor Specification Rev 6.xls]SPECIFICATION


ZETON VESSEL SPECIFICATION SHEET (VESSLSP6.XLS, REV. 5, OCT22/99)
SKETCH/ADDITIONAL INFORMATION
WEIGHT OF INTERNAL REFRACTORY AND CATALYST 13000 LBS
(TO BE CONFIRMED)
50" OD SHELL
50 PSIG @ 650F DESIGN
(SHELL BY VESSEL FABRICATOR)

ZETON VESSEL SPECIFICATION SHEET (VESSLSPS.XLS, REV. 5, OCT22/99)

TAG/ITEM: R-1 (REACTOR) CLIENT: PROJECT #: 757-20 DATE: 26-Aug-05 PAGE 3 OF 3
REV. NO. A

SKETCH/ADDITIONAL INFORMATION

THE FOLLOWING GENERAL SPECIFICATIONS SHALL BE FOLLOWED IN THE DESIGN AND FABRICATION OF THE VESSEL (S).

1) ZETON PRESSURE VESSEL GENERAL SPECIFICATION REV 6

2) ALL VESSELS ARE TO BE "U" AND "TSSA" REGISTERED.

3) ALL VESSELS ARE TO BE SPOT RADIOGRAPHED - THE GREATER OF TWO SPOTS PER WELDER OR THE ASME VIII REQUIREMENTS SHOULD BE SHOT PER VESSEL

THE MATERIAL SPECIFICATIONS ARE AS FOLLOWS:

COMPONENT	MATERIAL SPECIFICATION
TOP HEAD COVER	CS 1500# B16.47 BLIND FLANGE
TOP HEAD	CS 1500# B16.47 FLANGE
BOTTOM HEAD COVER	
BOTTOM HEAD	SA285-C OR SA516-70 PLATE
SHELL	SA285-C OR SA516-70 ROLLED PLATE
JACKET	
NOZZLES	SA106-B OR SA53-B WELDED SEAM PIPE
NOZZLE FLANGES	SA-105 1500# RFWN
PAD FLANGES	
FLANGE BOLTING	SA-193 B7
NUTS	SA-194 2H
NOZZLE GASKETS	
COVER GASKETS	FLEXITALLIC AF2100 NON ASBESTOS FIBRE GASKET OR NON ASBESTOS FIBRE GASKET OR 316SS TANGED METAL INSERTED GRAPHITE SHEET
SUPPORTS	SA-36, SA516-70
BAR/ROD STOCK	

FILENAME: H:\757-20\Reactor\[Reactor Specification Rev 0.xls]GEN SPECS MAT'L

APPENDIX K

ChevronTexaco SSR Design Temperatures / Materials
REV: 5
DATE: 26-Aug-05
FILE: H:\757-20\Design Temperature Materials\[Design Temperatures Materials Rev 5.xls]Design Temp Mat'l

From	To	Fluid	Max Operating Temp °C	Max Operating Temp °F	Design Temp °C	Design Temp °F	Piping Material	Line Size (inch)	Sch/Wall	Corrosion Allowance (inch)	Flange Rating	Notes
REGENERATION												
Atmosphere	Blower (C-1)	Air	43	110	66	150	A312-TP304/304L					
Blower (C-1)	Air Buffer Tank	Air	250	482	288	550	A312-TP304/304L Welded Seam Pipe	4	10S	0	150#	Compressor discharge temp per vendor quote
Air Buffer Tank	HX1 (Coldside Inlet)	Air	250	482	288	550	A312-TP304/304L Welded Seam Pipe	4	10S	0	150#	Compressor discharge temp per vendor quote
HX1 (Coldside Outlet)	Reactor/Burner	Air	800	1472	816	1500	A312-TP304H Welded Seam Pipe	4	40S	0.0625	600#	
Reactor	HX1 (Hotside Inlet)	Regen gas	800	1472	816	1500	A312-TP304H Welded Seam Pipe	4	40S	0.0625	600#	Common line with Reactor to HX2 during reforming.
HX1 (Hotside Outlet)	Vent	Regen gas	583	1081	649	1200	A312-TP304H Welded Seam Pipe	4	10S	0.0625	300#	
Natural Gas Supply	Reactor Burner	NG	43	110	66	150				0		
REFORMING												
Process NG supply	Fired Boiler Package	NG	43	110	66	150	A312-TP304/304L Welded Seam Pipe					
TV016108	HX-4 (Coldside Inlet)	Water	43	110	66	150	A269-TP316/316L Welded Seam Tube	0.5	0.049	0	Tubing	
HX-4 (Coldside Outlet)	Fired Boiler Package	Water	136	277	177	350	A269-TP316/316L Welded Seam Tube	0.5	0.049	0	Tubing	
Fired Boiler Package	Reactor	Steam+NG	800	1472	816	1500	A312-TP304H Welded Seam Pipe	2	40S	0.0625	600#	Above 1500F design temp, Incoloy 800H required (Incoloy 800H limited to 1650F design temperature). There are no flange ratings above 1500F.
Reactor	HX2 (Hotside Inlet)	Reformate	800	1472	816	1500	A312-TP304H Welded Seam Pipe	2	40S	0.0625	600#	Partly common line with Reactor to HX1 during regen.
HX-2 (Hotside Outlet)	HX-4 (Hotside Inlet)	Reformate	400	753	454	850	A312-TP304/304L Welded Seam Pipe	2	10S	0	150#	
HX-4 (Hotside Outlet)	Methanator	Reformate	400	753	454	850	A312-TP304/304L Welded Seam Pipe	1.5	10S	0	150#	
Methanator	HX3 (Hotside Inlet), Methanator Bypass	Reformate	420	788	454	850	A312-TP304/304L Welded Seam Pipe	1.5	10S	0	150#	
HX3 (Hotside Outlet)	Vent	Reformate	266	510	316	600	A312-TP304/304L Welded Seam Pipe	1.5	10S	0	150#	
Air Buffer Tank	HX3 (Coldside Inlet)	Air	250	482	288	550	A312-TP304/304L Welded Seam Pipe	1.5	10S	0	150#	Compressor discharge temp per vendor quote
HX3 (Coldside Outlet)	HX2 (Coldside Inlet)	Air	370	698	427	800	A312-TP304/304L Welded Seam Pipe	2	10S	0	150#	
HX2 (Coldside Outlet)	Fired Boiler Package	Air	617	1143	704	1300	A312-TP304H Welded Seam Pipe	2	10S	0.0625	300#	
Fired Boiler Package	Exhaust	Flue Gas	200	392	232	450	A312-TP304/304L Welded Seam Pipe	2	10S	0	150#	
Boiler	Superheater	Steam	136	277	177	350	A312-TP304/304L Welded Seam Pipe	1	10S	0	150#	
Boiler	Superheater	Steam+NG	136	277	177	350	A312-TP304/304L Welded Seam Pipe	1.5	10S	0	150#	
Natural Gas Header	Fired Boiler Package Superheater	NG	43	110	66	150	A269-TP316/316L Welded Seam Tube	0.75	0.065	0	Tubing	
Natural Gas Header	Fired Boiler Package Burner	NG	43	110	66	150	A269-TP316/316L Welded Seam Tube	0.5	0.049	0	Tubing	
Natural Gas Supply	Natural Gas Header (Fired Boiler Package Burner + Superheater)	NG	43	110	66	150						
REVERSE COOLING												
HX1	Reactor/Burner (Rev Cooling)	Air	300	572	371	700	A312-TP304/304L Welded Seam Pipe	4	10S	0	150#	[illegible]
Reactor	HX-2 (Hotside Inlet)	Air	800	1472	816	1500	A312-TP304H Welded Seam Pipe	4	40S	0.0625	600#	

APPENDIX L

Gas Pressure Drop Spreadsheet (GPDROP11.WK4, Rev 11, Oct 2/02)

CLIENT: Chevron Techology Ventures
PROJ NO: 757-20
FILE: Regeneration Air Pressure Drop Rev 3.WK4
REV: 3
TE: AUG 23, 2005
NE:

Bed Pressure Drop		
Bed Diameter	22.5	[inch]
Bed Volume	432	[litres]
Bed L/D	2.95	
Gas Density Aver	0.0460	[lb/ft3]
Gas Mass Velocity	0.3713	[lb/ft2/sec]
Bed Length	66.3	[inch]
Bed Void Fraction	0.4	
Gas Viscosity	0.0454	[cp]
Effect Particle Diam	0.125	[inch]
Bed Pres Drop	7.91	[psid]
20% Safety	1.58	
Total Bed Pres Drop	9.49	

Equipment Pressure Drop (psid)		
HX1 Coldside	4.30	
Reactor Bed + 20% Safety	9.49	
Gas Distributor Top	3.85	
Gas Distributor Bottom	3.85	
HX1 Hotside	4.10	
Regen Exh Cooler	0.90	
TOTAL	24.48	
Instrument / Control Valve Pressure Drop (psid)		
FE/PT-6301	7.23	
TV-6301	0.53	
TOTAL INSTR/CONT VALVE	7.76	
Discharge Piping Pressure Drop (psid)		
Piping	11.06	
15% Safety	1.66	(On Piping)
TOTAL PIPING	12.72	
Total Disch Pressure Drop (psig)	44.43	

Blower	
Blower Head (psid)	44.97
Blower Disch (psig)	44.97
Plant Outlet (psig)	0.00

Description	Fitting	Note	Qty	Pres In (psig)	Pres Out (psig)	Pres Drop (%)	Flow Value	Temp (F)	Temp (C)	MW	Z	Visc (cp)	Cp/Cv	Roughness (micro inches)
				0.00										
Air to Blower Suction	Pressure		—	0.0	0.0	—	1616	110	43	28.85	1	0.0194	1.4	pipe
BLOWER	Pr Drop = -44.97 psid		1	0.0	45.0	—	1616	110	43	28.85	1	0.0194	1.4	pipe
Blower Discharge	Pressure		—	44.97	45.0	—	1616	482	250	28.85	1	0.0278	1.4	pipe
Blower to HX-1 Coldside	Straight Length (Ft)		0.12	45.0	45.0	0	1616	482	250	28.85	1	0.0278	1.4	pipe
" "	Expansion (D out)		1	45.0	45.1	-0	1616	482	250	28.85	1	0.0278	1.4	pipe
" "	Straight Length (Ft)		60	45.1	44.5	0	1616	482	250	28.85	1	0.0278	1.4	pipe
" "	Elbow SW		10	44.9	44.7	0	1616	482	250	28.85	1	0.0278	1.4	pipe
" " (FE/PT-6301)	Pr Drop = 200 in WC		1	44.7	37.5	12	1616	482	250	28.85	1	0.0278	1.4	pipe
" " (TE-6301)	Misc Vel Head		1	37.5	37.5	0	1616	482	250	28.85	1	0.0278	1.4	pipe
" "	Tee (Run)		1	37.5	37.5	0	1616	482	250	28.85	1	0.0278	1.4	pipe
" " (AV-6301)	Ball Valve (Open)		1	37.5	37.4	0	1616	482	250	28.85	1	0.0278	1.4	pipe
" " (TV-6301)	CV = 200		1	37.4	36.9	1	1616	482	250	28.85	1	0.0278	1.4	pipe
" "	Tee (Run)		1	36.9	36.9	0	1616	482	250	28.85	1	0.0278	1.4	pipe
" "	Exit from Pipe (Pipe D)		1	36.9	36.9	0	1616	482	250	28.85	1	0.0278	1.4	pipe
HX1 COLDSIDE	Pr Drop = 4.30 psid		1	36.9	32.6	8	1616	938	504	28.85	1	0.0361	1.4	pipe
HX1 Coldside to Reactor	Entrance to Pipe (Pipe D)		1	32.6	32.3	1	1616	1395	757	28.85	1	0.0450	1.4	pipe
" "	Straight Length (Ft)		25	32.3	31.9	1	1616	1395	757	28.85	1	0.0450	1.4	pipe
" "	Elbow SW		8	31.9	31.5	1	1616	1395	757	28.85	1	0.0450	1.4	pipe
" " (TW-6605/6610)	Misc Vel Head		1	31.5	31.5	0	1616	1395	757	28.85	1	0.0450	1.4	pipe
" "	Tee (Run)		1	31.5	31.5	0	1616	1395	757	28.85	1	0.0450	1.4	pipe
" " (In-Line Mixer)	Pr Drop = 2.00 psid		1	31.5	29.5	4	1616	1395	757	28.85	1	0.0450	1.4	pipe
" " (AV-6602)	Ball Valve (Open)		1	29.5	29.2	0	1616	1395	757	28.85	1	0.0450	1.4	pipe
" "	Reduction (D out)		1	29.2	28.7	1	1616	1395	757	28.85	1	0.0450	1.4	pipe
" "	Straight Length (Ft)		0.458	28.7	28.7	0	1616	1395	757	28.85	1	0.0450	1.4	pipe
" " (CHK-2)	Swing Check (Straight)		1	28.7	28.1	1	1616	1395	757	28.85	1	0.0450	1.4	pipe
" "	Expansion (D out)		1	28.1	28.3	-1	1616	1395	757	28.85	1	0.0450	1.4	pipe
" " (FA-1)	2 Vel Hd Pr Drop = 0.43 psid		1	28.3	28.1	1	1616	1395	757	28.85	1	0.0450	1.4	pipe
" " (90 Tee)	Conv Tee (Run, QT)		1	28.1	28.0	0	1619	1395	757	28.85	1	0.0450	1.4	pipe
" " (Burner)	Pr Drop = 1.0 psid		1	28.0	27.0	2	1619	1395	757	28.85	1	0.0450	1.4	pipe
Burner Outlet	Expansion (D out)		1	27.0	27.0	0	1619	1872	1022	28.75	1	0.0456	1.4	pipe

Description	Nomin Diam (inches)	Sched/Wall (in/mm)	Angle (deg), X-Sect/X-Sect	R/D, Length (in), Min Vel (ft/s), Liq Dens (lb/ft3)	e/D (length/hdr)	ID (inch)	Vel Area (ft/s)		Vel Head (psi)	Vel Heads Per Fitting	DP 100 (psi per 100 ft)	Fitt Pres Drop (psig)	Err (%)	Dens (lb/ft3)	Sonic Vel (ft/sec)
Air to Blower Suction	4	10S	—	—	—	4.26	144	IN	0.155	—	—	—	—	0.06657	1172
BLOWER	4	10S	—	—	—	4.26	97	AV	0.061	-732	—	-44.962	—	0.17547	1172
Blower Discharge	3	10S	—	—	—	3.26	108	IN	0.185	—	—	—	—	0.17854	1507
Blower to HX-1 Coldside	3	10S	—	—	—	3.26	108	AV	0.185	0.068	1.37	0.00	0.00	0.17853	1507
" "	4	10S	Ang = 14.21	Len = 4.00	0.766	4.26	59	AV	0.063	0.167	—	0.00	—	0.17849	1507
" "	4	10S	—	—	—	4.26	59	AV	0.062	0.032	0.35	0.18	0.00	0.17836	1507
" "	4	10S	Ang = 90	R/D= 1.459	—	4.26	59	AV	0.063	0.243	—	0.15	—	0.16986	1507
" " (FE/PT-6301)	4	10S	—	—	—	4.26	65	AV	0.068	106.155	—	7.23	—	0.15903	1507
" " (TE-6301)	4	10S	Sm/A 0.001	Re' = 2.7E+005	—	4.26	67	AV	0.072	0.078	—	0.01	—	0.148	1507
" "	4	10S	—	—	—	4.26	67	AV	0.072	0.322	—	0.02	—	0.14896	1507
" " (AV-6301)	4	10S	Ang = 180	—	0.83	4.26	67	AV	0.072	0.506	—	0.04	—	0.14888	1507
" " (TV-6301)	4	10S	—	CV= 200	—	4.26	68	LM	0.073	7.327	—	0.53	—	0.14806	1507
" "	4	10S	—	—	—	4.26	68	AV	0.073	0.322	—	0.02	—	0.14727	1507
" "	4	10S	—	—	—	4.26	68	AV	0.066	1.000	—	0.07	—	0.14724	1507
HX1 COLDSIDE	4	10S	—	—	—	4.26	108	AV	0.111	37.896	—	4.3	—	0.09503	1837
HX1 Coldside to Reactor	4	40S	—	—	—	4.026	164	AV	0.198	0.500	—	0.10	—	0.06801	2115
" "	4	40S	—	—	—	4.026	165	AV	0.199	0.058	1.16	0.40	0.00	0.0678	2115
" "	4	40S	Ang = 90	R/D= 1.066	—	4.026	166	AV	0.201	0.250	—	0.37	—	0.06724	2115
" " (TW-6605/6610)	4	40S	Sm/A 0.015	Re' = 1.9E+005	—	4.026	167	AV	0.202	0.008	—	0.00	—	0.06695	2115
" "	4	40S	—	—	—	4.026	168	AV	0.202	0.326	—	0.10	—	0.06678	2115
" " (In-Line Mixer)	4	40S	—	—	—	4.026	172	AV	0.207	9.645	—	2	—	0.06539	2115
" " (AV-6602)	4	40S	Ang = 180	—	0.82	4.026	176	AV	0.212	0.507	—	0.11	—	0.06366	2115
" "	3	40S	Ang = 12.00	Len = 4.00	0.762	3.068	305	AV	0.634	0.040	—	0.03	—	0.06326	2115
" "	3	40S	—	—	—	3.068	306	AV	0.637	0.076	4.87	0.02	0.00	0.06291	2115
" " (CHK-2)	3	40S	—	Vel = 240.02	—	3.068	306	AV	0.641	0.896	—	0.56	—	0.06249	2115
" "	4	40S	Ang = 12.00	Len = 4.00	0.762	4.026	179	AV	0.217	0.161	—	0.03	—	0.06217	2115
" " (FA-1)	4	40S	—	—	—	4.026	180	AV	0.217	2.000	—	0.43	—	0.06234	2115
" " (90 Tee)	4	40S	—	Qb/QT= 0.9679	—	4.026	181	AV	0.210	0.325	—	0.07	—	0.06197	2115
" " (Burner)	4	40S	—	—	—	4.026	183	AV	0.222	4.500	—	1	—	0.06119	2115
Burner Outlet	22.5		Ang = 180	Len = 0.00	0.1789	22.5	5	AV	0.000	514.031	—	0.25	—	0.05561	2218

1 OF %

Gas Pressure Drop Spreadsheet (GPDROP11.WK4, Rev 11, Oct 2/02)

CLIENT:	Chevron Techology Ventures
PROJ NO:	757-20
FILE:	Regeneration Air Pressure Drop Rev 3.WK4
REV:	3
ATE:	AUG 25, 2005
AE:	

Bed Pressure Drop		
Bed Diameter	22.5	[inch]
Bed Volume	432	[litres]
Bed L/D	2.95	
Gas Density Aver	0.0460	[lb/ft3]
Gas Mass Velocity	0.3713	[lb/ft2/sec]
Bed Length	66.3	[inch]
Bed Void Fraction	0.4	
Gas Viscosity	0.0454	[cp]
Effect Particle Diam	0.125	[inch]
Bed Pres Drop	7.91	[psid]
20% Safety	1.58	
Total Bed Pres Drop	9.49	

Equipment Pressure Drop (psid)		
HX1 Coldside	4.30	
Reactor Bed + 20% Safety	9.49	
Gas Distributor Top	2.85	
Gas Distributor Bottom	2.85	
HX1 Hotside	4.10	
Regen Exh Cooler	0.90	
TOTAL	24.48	
Instrument / Control Valve Pressure Drop (psid)		
FE/FT-6301	7.23	
TV-6301	0.53	
TOTAL INSTR/CONT VALVE	7.76	
Discharge Piping Pressure Drop (psid)		
Piping	11.06	
15% Safety	1.66	(On Piping)
TOTAL PIPING	12.72	
Total Disch Pressure Drop (psig)	44.43	

Blower	
Blower Head (psid)	44.97
Blower Disch (psig)	44.97
Plant Outlet (psig)	0.00

Description	Fitting	No. (x)	Qty	Pres In (psig)	Pres Out (psig)	Pres Drop (%)	Flow Value	Temp (F)	Temp (C)	MW	Z	Visc (cp)	Cp/Cv	Roughness (micro-inches)	Nomin (Size) (inches)	Sched/Wall (inches)	Angle (deg), X-sect/X-sect	R/D, Length (in), Max Vel (ft/s), Liq Dens (lb/ft3)	d/D (small/big)	ID (inch)	Vel Avrg (ft/s)		Vel Head (psi)	Vel Heads Per Fitting	DP 100 (psi per 100 ft)	Frict Pres Drop (psig)	Err (%)	Dens (lb/ft3)	Sonic Vel (ft/sec)
TOP GAS DISTRIB (30% of BED)	Pr Drop = 2.85 psid		1	27.6	26.2	7	1674	1572	856	28.75	1	0.0454	1.4	pipe	22.5	0	----	----	----	22.5	7	AV	0.000	10162	----	2.85	----	0.05313	2218
REACTOR BED	Pr Drop = 7.91 psid		1	24.3	16.5	28	1674	1572	856	28.75	1	0.0454	1.4	pipe	22.5	0	----	----	----	22.5	8	AV	0.000	14463	----	7.91	----	0.04903	2218
" " (20% Safety of Bed)	Pr Drop = 1.58 psid		1	16.5	14.7	5	1674	1572	856	28.75	1	0.0454	1.4	pipe	22.5	0	----	----	----	22.5	9	AV	0.000	4028	----	1.58	----	0.03978	2218
BOT GAS DISTRIB (30% of BED)	Pr Drop = 2.85 psid		1	14.7	11.8	18	1674	1572	856	28.7547	1	0.0454	1.4	pipe	22.5	0	----	----	----	22.5	10	AV	0.000	********	----	2.85	----	0.03586	2218
Reactor to HX-1 Hotside	Exit from Vessel (Pipe D)		1	11.8	11.2	2	1674	1472	800	28.75	1	0.0441	1.4	pipe	4	40S	----	----	----	4.026	319	AV	0.390	0.500	----	0.20	----	0.03637	2162
" "	Straight Length (ft)		42	11.2	10.1	4	1674	1472	800	28.75	1	0.0441	1.4	pipe	4	40S	----	----	----	4.026	329	AV	0.413	0.858	1.36	1.87	8.69	0.03352	2162
" "	Elbow RW		2	10.1	9.2	3	1674	1472	800	28.75	1	0.0441	1.4	pipe	4	40S	Ang = 90	R/D= 1.490011	----	4.026	341	AV	0.428	0.270	----	0.79	----	0.03289	2162
" " (AV-6604)	Ball Valve (Open)		1	9.2	9.1	1	1674	1472	800	28.7547	1	0.0441	1.4	pipe	4	40S	Ang = 180	----	0.85	4.026	350	AV	0.438	0.507	----	0.22	----	0.03317	2162
" "	Tee (Run)		2	9.1	8.8	1	1674	1472	800	28.7547	1	0.0441	1.4	pipe	4	40S	----	----	----	4.026	355	AV	0.442	0.126	----	0.29	----	0.03281	2162
" " (TW-6608/6611)	Misc Vel Head		2	8.8	8.7	0	1674	1472	800	28.7547	1	0.0441	1.4	pipe	4	40S	Sm/A 0.015	Re = 2.0E+005	----	4.026	356	AV	0.446	0.020	----	0.06	----	0.03256	2162
" "	Exit from Pipe (Pipe D)		1	8.7	8.7	0	1674	1472	800	28.75	1	0.0441	1.4	pipe	4	40S	----	----	----	4.026	357	AV	0.000	1.000	----	0.45	----	0.03252	2162
HX1 HOTSIDE	Pr Drop = 4.10 psid		1	8.7	4.6	17	1674	1000	560	28.75	1	0.0278	1.4	pipe	4	40S	----	----	----	4.026	385	AV	0.180	10.798	----	4.10	----	0.03823	1965
HX1 Hotside to Exhaust Cooler	Entrance to Pipe (Pipe D)		1	4.6	4.3	2	1674	608	320	28.75	1	0.0303	1.4	pipe	4	10S	----	----	----	4.26	215	AV	0.241	0.500	----	0.32	----	0.04811	1607
" "	Straight Length (ft)		30	4.3	3.9	2	1674	608	320	28.75	1	0.0303	1.4	pipe	4	10S	----	----	----	4.26	220	AV	0.246	0.052	1.29	0.39	8.69	0.04716	1607
" "	Elbow RW		2	3.9	3.5	2	1674	608	320	28.75	1	0.0303	1.4	pipe	4	10S	Ang = 90	R/D= 1.0084507	----	4.26	225	AV	0.251	0.245	----	0.45	----	0.04613	1607
" " (AV-1612)	Ball Valve (Open)		1	3.5	3.3	1	1674	608	320	28.7547	1	0.0303	1.4	pipe	4	10S	Ang = 180	----	0.85	4.26	228	AV	0.255	0.506	----	0.13	----	0.04562	1607
" " (TW-1612)	Misc Vel Head		1	3.3	3.3	0	1674	608	320	28.7547	1	0.0303	1.4	pipe	4	10S	Sm/A 0.014	Re = 2.5E+005	----	4.26	229	AV	0.256	0.020	----	0.02	----	0.04527	1607
" "	Exit from Pipe (Pipe D)		1	3.3	3.3	0	1674	608	320	28.75	1	0.0303	1.4	pipe	4	10S	----	----	----	4.26	229	AV	0.000	1.000	----	0.26	----	0.04521	1607
REGEN EXHAUST COOLER	Pr Drop = 0.90 psid		1	3.3	2.4	5	1674	374	190	28.75	1	0.0256	1.4	pipe	4	10S	----	----	----	4.26	184	AV	0.305	4.387	----	0.90	----	0.05644	1420
Regen Exhaust Cooler to Exhaust	Entrance to Pipe (Pipe D)		1	2.4	2.2	1	1674	140	60	28.75	1	0.0201	1.4	pipe	4	10S	----	----	----	4.26	136	AV	0.153	0.500	----	0.08	----	0.07595	1205
" "	Straight Length (ft)		30	2.2	1.9	1	1674	140	60	28.75	1	0.0201	1.4	pipe	4	10S	----	----	----	4.26	138	AV	0.155	0.050	0.76	0.23	8.68	0.07489	1205
" "	Elbow RW		2	1.9	1.7	2	1674	140	60	28.75	1	0.0201	1.4	pipe	4	10S	Ang = 90	R/D= 1.0084507	----	4.26	140	AV	0.157	0.245	----	0.27	----	0.07376	1205
" " (TW-????)	Misc Vel Head		1	1.7	1.7	0	1674	140	60	28.7547	1	0.0201	1.4	pipe	4	10S	Sm/A 0.014	Re = 3.5E+005	----	4.26	142	AV	0.158	0.020	----	0.01	----	0.07313	1205
" "	Exit from Pipe (Pipe D)		1	1.7	1.7	0	1674	140	60	28.75	1	0.0201	1.4	pipe	4	10S	----	----	----	4.26	142	AV	0.000	1.000	----	0.16	----	0.07313	1205
15% SAFETY ON PIPING	Pr Drop = 1.66 psid		1	1.7	0.0	10	1674	140	60	28.75	1	0.0201	1.4	pipe	4	10S	----	----	----	4.26	149	AV	0.167	9.943	----	1.7	----	0.0694	1205
	END CONDITIONS			0.00	0.0		1674	140	60	28.75	1	0.0201	1.4	pipe	4	10S				4.26	158	OT	0.176					0.06599	1205

Pressure Drop (psi)	-0.00
Base ID (inch)	4.26
Base Roughness (µin)	2500
Equivalent Length (ft)	8,455.94

Qty Units:	kg
Time Units:	hr

STAND COND:	
Pressure (psia)	14.696
Temp (deg F)	60
ATMOS PRESSURE (psia)	14.7

2 OF %

Gas Pressure Drop Spreadsheet (GPDROP11.WK4, Rev 11, Oct 2/02)

CLIENT:	Chevron Technology Ventures		Equipment Pressure Drop (psid)	
PROJ NO:	757-20		HX3 Coldside	2.00
FILE:	Reforming Air Pressure Drop Rev 3.WK4		HX2 Coldside	2.10
REV:	3		Fired Boiler Package	4.00
TE:	AUGUST 20, 2005		Instrument / Control Valve Pressure Drop (psid)	
..E:			FE/FT-6301	0.30
Blower			Discharge Piping (psid)	
Blower Head (psid)	24.98		Piping	14.42
Blower Disch (psig)	24.98		15% Safety	2.16 (On Piping)
Blower Inlet (m3/h)	256.0		TOTAL PIPING	16.58
Discharge Pres (bar g)	1.72		Total Disch Pressure Drop (psig)	24.98
Plant Outlet (psig)	-0.00			

Description	Piping	No. in	Qty	Pres In	Pres Out	Pres Drop	Flow Value	Temp (F)	Temp (C)	MW	Z	Visc (cP)	Cp/Cv	Roughness (micro	Nomin Diam	Sched/ Wall	Angle (deg), K-Sect/X-Sect	K/D, Length (in), Min Vel (ft/s)	e/D (small)	ID (inch)	Vel Aver		Vel Head	Vel Heads Fit	DP 100 (psi) per	Fitt Pres Drop	Err (%)	Dens	Sonic Vel
				0.09																									
Air to Blower Suction	Pressure		----	0.0	0.0	----	329	110	43	28.85	1	0.0194	1.4	pipe	4	10S	----	----	----	4.26	29	IN	0.060	----	----	----	----	0.06917	1172
BLOWER	Pr Drop = -24.98 psid		1	0.0	25.0	----	329	110	43	28.85	1	0.0194	1.4	pipe	4	10S	----	----	----	4.26	16	AV	0.062	-7171	----	[illegible]	----	0.1283	1172
Blower Discharge	Pressure		----	24.98	25.0	----	329	313	157	28.85	1	0.0242	1.4	pipe	3	10S	----	----	----	3.26	25	IN	0.009	----	----	----	----	0.13776	1367
Blower to HX3 Coldside	Straight Length (Ft)		2.25	25.0	25.0	0	329	313	157	28.85	1	0.0242	1.4	pipe	3	10S	----	----	----	3.26	25	AV	0.009	0.082	0.88	0.00	0.09	0.13778	1367
" "	Expansion (D out)		1	25.0	25.0	-0	329	313	157	28.85	1	0.0242	1.4	pipe	4	10S	Ang = 14.25	Len = 4.00	0.765	4.26	15	AV	0.003	0.161	----	0.00	----	0.13777	1367
" "	Straight Length (Ft)		60	25.0	25.0	0	329	313	157	28.85	1	0.0242	1.4	pipe	4	10S	----	----	----	4.26	15	AV	0.003	0.064	0.02	0.01	0.00	0.13775	1367
" "	Elbow LW		10	25.0	25.0	0	329	313	157	28.85	1	0.0242	1.4	pipe	4	10S	Ang = 90	R/D= 1.408	----	4.26	15	AV	0.003	0.241	----	0.01	----	0.13772	1367
" " (FE/FT-6301)	Pr Drop = 8 in WC		1	25.0	24.7	1	329	313	157	28.85	1	0.0242	1.4	pipe	4	10S	----	----	----	4.26	15	AV	0.003	91.920	----	0.30	----	0.13719	1367
" " (TE-6301)	Misc Vel Head		1	24.7	24.7	0	329	313	157	28.85	1	0.0242	1.4	pipe	4	10S	SmA 0.014	Re' = 0.2E+004	----	4.26	15	AV	0.003	0.078	----	0.00	----	0.13667	1367
" "	Red Tee (Run to Br, D Br)		1	24.7	24.3	1	329	313	157	28.85	1	0.0243	1.4	pipe	1.5	10S	----	----	0.3949	1.682	96	AV	0.134	1.364	----	0.31	----	0.13607	1367
" "	Straight Length (Ft)		20	24.3	23.7	2	329	313	157	28.85	1	0.0242	1.4	pipe	1.5	10S	----	----	----	1.682	97	AV	0.137	0.158	2.17	0.65	0.08	0.13434	1367
" "	Elbow LW		2	23.7	23.4	1	329	313	157	28.85	1	0.0242	1.4	pipe	1.5	10S	Ang = 90	R/D= 1.238	----	1.682	98	AV	0.139	0.318	----	0.31	----	0.13267	1367
" " (AV-6302)	Ball Valve (Open)		1	23.4	23.3	0	329	313	157	28.85	1	0.0242	1.4	pipe	1.5	10S	Ang = 180	----	0.02	1.682	99	AV	0.139	0.328	----	0.07	----	0.132	1367
" "	Exit from Pipe (Pipe D)		1	23.3	23.3	0	329	313	157	28.85	1	0.0242	1.4	pipe	1.5	10S	----	----	----	1.682	98	AV	0.006	1.000	----	0.14	----	0.13187	1367
HX3 COLDSIDE	Pr Drop = 2.00 psid		1	23.3	21.3	5	329	986	[illegible]	28.85	1	0.0282	1.4	pipe	1.5	10S	----	----	----	1.682	127	AV	0.179	11.196	----	2	----	0.10293	1527
HX3 Coldside to HX2 Coldside	Entrance to Pipe (Pipe D)		1	21.3	21.2	0	329	698	370	28.85	1	0.0320	1.4	pipe	2	10S	----	----	----	2.157	96	AV	0.081	0.500	----	0.04	----	0.08347	1671
" "	Straight Length (Ft)		40	21.2	20.7	1	329	698	370	28.85	1	0.0320	1.4	pipe	2	10S	----	----	----	2.157	96	AV	0.082	0.126	1.04	0.41	0.00	0.0828	1671
" "	Elbow LW		1	20.7	20.6	0	329	698	370	28.85	1	0.0320	1.4	pipe	2	10S	Ang = 90	R/D= 1.331	----	2.157	97	AV	0.082	0.288	----	0.17	----	0.08213	1671
" " (TW-6602)	Misc Vel Head		1	20.6	20.6	0	329	698	370	28.85	1	0.0320	1.4	pipe	2	10S	SmA 0.034	Re' = 1.9E+005	----	2.157	97	AV	0.083	0.070	----	0.03	----	0.08193	1671
" "	Tee (Run)		1	20.6	20.5	0	329	698	370	28.85	1	0.0320	1.4	pipe	2	10S	----	----	----	2.157	97	AV	0.083	0.776	----	0.02	----	0.08188	1671
" "	Exit from Pipe (Pipe D)		1	20.5	20.5	0	329	698	370	28.85	1	0.0320	1.4	pipe	2	10S	----	----	----	2.157	97	AV	0.000	1.000	----	0.08	----	0.08185	1671
HX2 COLDSIDE	Pr Drop = 2.10 psid		1	20.5	18.4	6	329	[illegible]	[illegible]	28.85	1	0.0288	1.4	pipe	2	10S	----	----	----	2.157	119	AV	0.102	20.575	----	2.1	----	0.06681	1825
HX2 Coldside to Fired Boiler Pk	Entrance to Pipe (Pipe D)		1	18.4	18.3	1	329	1140	617	28.85	1	0.0354	1.4	pipe	2	10S	----	----	----	2.157	145	AV	0.121	0.500	----	0.06	----	0.05543	1966
" "	Straight Length (Ft)		40	18.3	17.6	2	329	1140	617	28.85	1	0.0354	1.4	pipe	2	10S	----	----	----	2.157	145	AV	0.124	0.130	1.61	0.64	0.00	0.05473	1966
" "	Elbow LW		2	17.6	17.4	1	329	1141	617	28.85	1	0.0354	1.4	pipe	2	10S	Ang = 90	R/D= 1.331	----	2.157	147	AV	0.126	0.288	----	0.25	----	0.05399	1966
" "	Tee (Run)		1	17.4	17.3	0	329	1141	617	28.85	1	0.0354	1.4	pipe	2	10S	----	----	----	2.157	148	AV	0.127	0.276	----	0.05	----	0.05374	1966
" " (TW-6603/6604)	Misc Vel Head		2	17.3	17.3	0	329	1142	617	28.85	1	0.0354	1.4	pipe	2	10S	SmA 0.034	Re' = 1.5E+005	----	2.157	148	AV	0.127	0.050	----	0.01	----	0.05369	1966
" "	Reduction (D out)		1	17.3	17.1	1	329	1140	617	28.85	1	0.0354	1.4	pipe	1.5	10S	Ang = 9.06	Len = 3.00	0.7798	1.682	244	AV	0.344	0.023	----	0.01	----	0.05348	1966
" "	Straight Length (Ft)		2.448	17.1	17.0	0	329	1142	617	28.85	1	0.0354	1.4	pipe	1.5	10S	----	----	----	1.682	245	AV	0.345	0.166	5.73	0.03	0.00	0.05327	1966
" " (CHK-8)	Lift Check (Open)		1	17.0	7.4	38	329	1142	617	28.85	1	0.0354	1.4	pipe	1.5	10S	----	Vel = 135.90	0.85	1.682	368	AV	0.407	23.590	----	9.48	----	0.04517	1966
" "	Expansion (D out)		1	7.4	7.7	-1	329	1143	617	28.85	1	0.0354	1.4	pipe	2	10S	Ang = 9.06	Len = 3.00	0.7798	2.157	253	AV	0.182	0.085	----	0.02	----	0.03723	1966
" " (FA-3)	2 Vel Hd Pr Drop = 0.36 psid		1	7.7	7.5	2	329	1143	617	28.85	1	0.0354	1.4	pipe	2	10S	----	----	----	2.157	253	AV	0.182	2.000	----	0.36	----	0.03728	1966
" " (NG Tee)	Conv Tee (Run, GT)		1	7.5	7.5	0	333	1143	617	28.85	1	0.0354	1.4	pipe	2	10S	----	QB/QT= 0.5879	----	2.157	218	AV	0.189	0.578	----	0.07	----	0.03669	1966
FIRED BOILER PACKAGE	Pressure		----	7.5	7.5	----	333	1143	617	28.85	1	0.0354	1.4	pipe	2	10S	----	----	----	2.157	218	IN	0.189	----	----	----	----	0.03684	1966
" " (Burner)	Pr Drop = 1.0 psid		1	7.5	6.5	5	333	1143	617	28.85	1	0.0354	1.4	pipe	2	10S	----	----	----	2.157	233	AV	0.194	5.167	----	1	----	0.036	1966
" "	Exit from Pipe (Pipe D)		1	6.5	6.5	0	333	1143	617	28.85	1	0.0354	1.4	pipe	2	10S	----	----	----	2.157	229	AV	0.000	1.000	----	0.20	----	0.03516	1966
" " (Fired Boiler)	Pr Drop = 3.0 psid		1	6.5	3.5	14	333	1143	617	28.85	1	0.0354	1.4	pipe	2	10S	----	----	----	2.157	246	AV	0.213	14.037	----	3	----	0.03260	1966
Fired Boiler to Burner Exhaust	Entrance to Pipe (Pipe D)		1	3.5	3.1	1	333	392	200	28.53	1	0.0260	1.4	pipe	2	10S	----	----	----	2.157	144	AV	0.125	0.500	----	0.06	----	0.05576	1442
" "	Straight Length (Ft)		40	3.1	2.4	4	333	392	200	28.53	1	0.0260	1.4	pipe	2	10S	----	----	----	2.157	147	AV	0.128	0.123	1.57	0.63	0.00	0.05448	1442
" "	Elbow LW		1	2.4	2.2	1	333	392	200	28.53	1	0.0260	1.4	pipe	2	10S	Ang = 90	R/D= 1.3508200	----	2.157	151	AV	0.131	0.288	----	0.20	----	0.05307	1442
" " (TE-5604)	Misc Vel Head		1	2.2	2.2	0	333	392	200	28.53	1	0.0260	1.4	pipe	2	10S	SmA 0.013	Re' = 1.3E+005	----	2.157	153	AV	0.132	0.033	----	0.01	----	0.05264	1442
" "	Exit from Pipe (Pipe D)		1	2.2	2.2	0	333	392	200	28.53	1	0.0260	1.4	pipe	2	10S	----	----	----	2.157	157	AV	0.000	1.000	----	0.13	----	0.05263	1442
15% SAFETY ON PIPING	Pr Drop = 2.16 psid		1	2.2	-0.0	13	333	392	200	28.53	1	0.0260	1.4	pipe	2	10S	----	----	----	2.157	163	AV	0.141	15.287	----	2.2	----	0.04925	1442
	END CONDITIONS			-0.00	-0.0		333	392	200	28.53	1	0.0260	1.4	pipe	2	10S				2.157	175	OT	0.152					0.04588	1442

Pressure Drop (psid)	0.06
ID (inch)	2.157
Line Roughness (micro)	pipe
Equivalent Length (Ft)	2626.76

Qty Units: kg
Time Units: hr

STAND COND:
Pressure (psia): 14.696
Temp (deg F): 60
ATMOS PRESSURE (psia): 14.2

1 OF 16

APPENDIX M

ALPSWELDINGLIMITED
266 NORTH RIVERMEDE RD. CONCORD, ONT. L4K 3N6 TEL: (905) 669-2780 OR (416) 969-8190 FAX: (416) 969-8290

Aug. 31, 2005

ALPS QUOTE #: 05-6836

rev. 1

ZETON INC
740 Oval Court
Burlington, Ontario
L7L 6A9
Tel 905-632-3123 Ext. 227
Fax 905-632-0301

ATT'N: **Troy Wong**
Reference: Quotation, Zeton Job # 757-20

WE ARE PLEASED TO QUOTE ON THE FOLLOWING:

To supply material as noted, design, register, fabricate and test to ASME Code Section VIII Div.1, latest Edition and your RFQ dated Aug. 26, 2005:

One Only Reactor: 50"O.D. X Approx. 12'-8"" Str. –Material of Construction C/Steel
Per Zeton Vesel Spec. Sheet (Vesslsp5.xls, rev.5, OCT22/99) Rev. A-Dated Aug.26, 2005

For a price of ....$ 38, 500.00 ea.

Please note that the above price is based on the following:

- We assume that these vessels are not intended for lethal service.
- Thermal and process design to be done by Zeton. Alps will provide ASME calculation based on the design pressure of 50 PSIG @ 650 Deg. F.
- Alps Welding to supply all material <u>**except**</u> the following items: Cover flange with all nozzles and burner, as shown on the drawing, Insulation and insulation supports (including metal cap on end of insulation), arched catalyst support (design, supply and installation by others), Transition connections-12" spools-304H material, Bolting and gaskets for these spools, Insulation pins.
- Our price includes Bolting B7/ 2H for 50"-150 # Flange and Five (5) Non-Asbestos Fiber gaskets for this flange.
- Our price includes welding of insulation pins. Pins to be supplied by Zeton-195 Pieces, as you specified.
- Internal and External weld finish: flux, spatter and stain removed.
- Internal and External surface finish: Std. Mill finish.
- Blasting and painting are NOT included in our price
- For NDE we allowed for X-Ray only.

Terms: Progress payments to be negotiated.
Delivery: Approx. 12 weeks after receipt of PO and approved for construction drawings.
F.o.b.: Alps Welding Ltd.
Taxes: Extra if applicable.
Quote validity: 10 days

Sincerely,
Srdjan Vuceljic

Custom Metal Fabricators:
Stainless Steel Alloys, Carbon Steel, Aluminum
Custom Cutting Services
Industrial Installation Repair

Certified By:
T.S.S.A., ASME,("U")

08-31-05 10:06 MAXON INDUSTRIAL ID=9057951819 P.01

PROPOSED BILL OF MATERIAL

MAXON CORPORATION

P.O.Box 2068, Muncie, Indiana, U.S.A. 47307-0068
201 East 18th Street, Muncie, Indiana, U.S.A. 47302-4124
http://www.maxoncorp.com

Corporate Offices
PHONE: (765) 284-3304
FAX: (765) 286-8394
DUN-S: 00-641-3774
FED.ID.#:35-0496620

SALES PROPOSAL

No.	CUSTOMER NO.	DATE	PAGE
355949 SP	99999999	08/30/05	1

FAXED

5 ~~4~~ PAGES

FOR → ZETON INC.
740 OVAL COURT
ATTN: TROY WONG
BURLINGTON ON L7L 6A9
CANADA

RESPOND TO:
Maxon Industrial Equipment
6375 Dixie Road, Unit 3
Mississauga, Ontario L5T 2E1

PHONE (905) 795-0717
FAX (905) 795-1819

TERRITORY	REQUESTED BY	TERMS	DELIVERY INSTRUCTIONS
124	TROY WONG	TERMS TO BE ESTABLISHED	PER TERMS AND CONDITIONS ATTACHED

NOTES: Prices in U.S. funds, F.O.B. Indiana

- IMPORTANT - THE GOODS DESCRIBED HEREIN ARE PURCHASED ACCORDING TO TERMS AND CONDITIONS SET FORTH.

QTY.	ITEM NO.	DESCRIPTION	UNIT PRICE	EXTENSION
1.0	LV5B24	LV-5B-24 LV AIRFLO BURNER AL BRZ BDY. HA-X MXG PLT		
		********** LV-5B-24 LV AIRFLO BRNR+ ************************* 6" STRAIGHT (-6)............. 1 PLAIN END PLATE SET........... 1 MAX APPROACH AIR TEMP (F)..... 1050F Approach Air Temp (Max) BODY FLANGE KITS.............. 2 2" END INLET FLANGE KIT....... 1 CONNECTIONS................... ANSI Threaded ********** LV5B CNFGD 2" END INLT FLG *********************** 2" NPT W/18075 (14MM) IGNITOR. 1 1050F BODY FLANGE KIT (A-286). 1		
1.0	18117	7.125" MINI FLAME ROD		
2.0	39790	ELECT FEEDTHROUGH INSULATOR		
1.0	.75-3SBB	3/4" DOUBLE BLOCK GAS TRAIN		
		********** CNFGD .75" STRAIGHT DOUBLE BLOCK TRAIN ********** PIPETRAIN VOLTAGE............ 115V/1PHASE/60HZ FLOW DIRECTION............... VERTICAL INLET LEFT TO RIGHT INLET GAS VALVE / COCK........ NEO BALL VALVE DRIPLEG...................... INCLUDE STRAINER..................... INCLUDE INLET PRESSURE GAUGE ASSEMBLY. 0-60 PSI INLET PRESSURE GAUGE PILOT........................ DO NOT INCLUDE MAIN GAS REGULATOR SIZE....... .75" REGULATOR PRESSURE SWITCHES............ NEMA 12 PRESSURE SWITCHES MAIN VALVE................... 5000 VLV CNGFD VENT VALVE................... VENT VALVE NOT REQUIRED BLOCKING VALVE............... 5000 VLV CNGFD OUTLET PRESSURE GAUGE........ 0-60 PSI PRESSURE GAUGE OUTLET GAS VALVE / COCK....... HOMESTEAD LUBE GAS COCK ********** CNFGD LP NEMA12 PRESS SW ************************* ASHCROFT..................... Ash B400 0-60PSI N4 1060769 ********** CNFGD HP NEMA12 PRESS SW ************************* ASHCROFT..................... Ash B400 0-60PSI N4 1060769		

CONTINUED

08-31-05 10:07 MAXON INDUSTRIAL ID=9057951819 P.02

PROPOSED BILL OF MATERIAL

MAXON CORPORATION
P.O.Box 2068, Muncie, Indiana, U.S.A. 47307-0068
201 East 18th Street, Muncie, Indiana, U.S.A. 47302-4124
http://www.maxoncorp.com

Corporate Offices
PHONE: (765) 284-3304
FAX: (765) 286-8394
D-U-N-S: 00-641-9774
FED.ID.#:35-0496620

SALES PROPOSAL

No.	CUSTOMER NO.	DATE	PAGE
355949 SP	99999999	08/30/05	2

FOR
ZETON INC.
740 OVAL COURT
ATTN: TROY WONG
BURLINGTON ON L7L 6A9
CANADA

RESPOND TO:
Maxon Industrial Equipment
6375 Dixie Road, Unit 3
Mississauga, Ontario L5T 2E1
PHONE (905) 795-0717
FAX (905) 795-1819

TERRITORY	REQUESTED BY	TERMS	DELIVERY INSTRUCTIONS
124	TROY WONG	TERMS TO BE ESTABLISHED	PER TERMS AND CONDITIONS

NOTES

QTY	ITEM NO.	DESCRIPTION	UNIT PRICE	EXTENSION
1.0	SI PNL	STANDARD INTER CONTROL PANEL		
		********** CNFGD STD INTER PNL ****************************** ENCLOSURE TYPE................ NEMA 12 Indoor Use Enclosure FLAME DETECTION............... Flame Rod (not supplied) SHIP LOOSE KIT (inc w/order).. Include with order SOFTWARE VERSION.............. Version 1 THERMOCOUPLE TYPE............. 0-2700 Degrees F ********** CNFGD PRE-PROGD 120V PLC+ ********************** SOFTWARE VERSION.............. Version 1 ********** CNFGD PNL SHIP LS KIT **************************** ENCLOSURE TYPE................ NEMA 12 Indoor Use Enclosure IGNITION TRANSFORMER.......... Include with order THERMOCOUPLE TYPE............. 0-2300F Thermocouple THERMOCOUPLE WIRE LENGTH (FT). 25ft of wire provided CONTROL MOTOR................. 150in-lb Honeywell Ctl Motor		
1.0	.5050 SYNCHRO	.5"-0-50 CONTROL VALVE		
		********** .5"-0-50 CNFGD SYNCHRO OIL VLV ***************** TRIM CHOICE................... Std CAM STYLE..................... Std cam VALVE BODY TYPE............... STD 350F CONN BASE & LINKAGE........... Hwell electric Modutrol SWITCH........................ Weatherproof low position TORQUE REQUIREMENT @ 10 PSIG.. 125 TORQUE REQUIREMENT @ 250 PSIG. 220		
1.0	095 PKGD SYS PR	PACKAGED SYSTEM PRICE	13,200.00 Per EA	13,200.00

U.S. funds

* SEE CATALOG SECTION 5400,6100,9720 FOR PROPER OPERATION *

NOTES: PRESENT DELIVERY IS 6 TO 8 WEEKS
PRICES QUOTED ARE IN U.S. FUNDS
F.O.B. MUNCIE, INDIANA, U.S.A.

*Freight, GST brokerage extra

THANK-YOU,

GLEN G. GRAY, P.ENG., SALES ENGINEER.

U.S.

- IMPORTANT - THE GOODS DESCRIBED HEREIN ARE PURCHASED ACCORDING TO TERMS AND CONDITIONS SET FORTH.

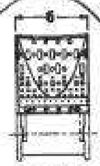
FREIGHT CHARGES AND SALES TAX WILL BE ADDED AT TIME OF INVOICING IF APPLICABLE.

SALES TAX @ % .00

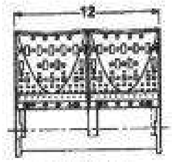
USD Dollar TOTAL 13,200.00

Dimensions (in inches)

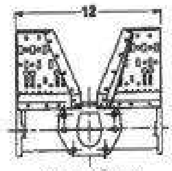
Series LV-3, -4, and -5 AIRFLO® Burner sections



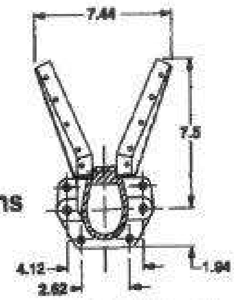
6" straight



12" straight

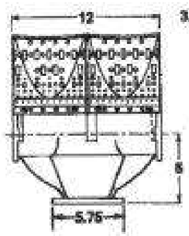


12" x 6" tee

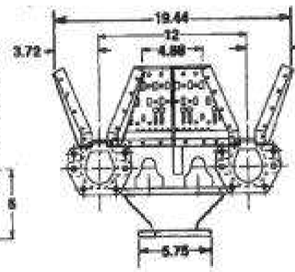


Typical End View of Straight Sections

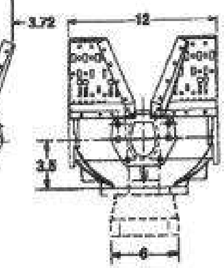
Series LV-3, -4, and -5 AIRFLO® Burner back inlet sections



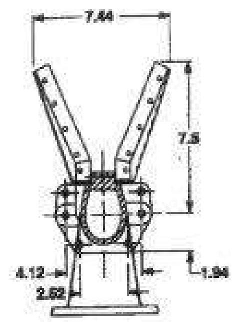
12" back inlet straight



36" back inlet

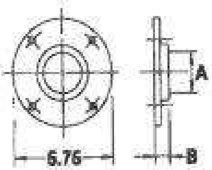


12" x 12" back inlet cross



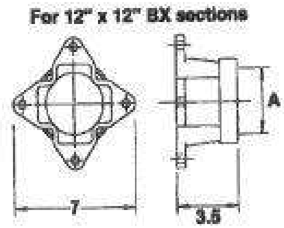
Inlet flange options

For 12" B & 36" BH sections



A Size	B
2" NPT	0.88
3" NPT	1.75

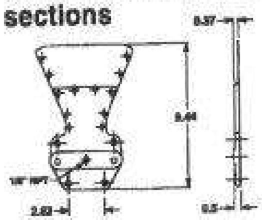
For 12" x 12" BX sections



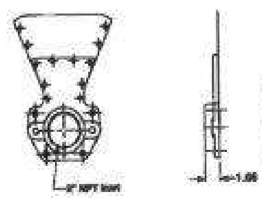
Size	A
3" NPT	3
4" NPT	4

Dimensions (in inches)

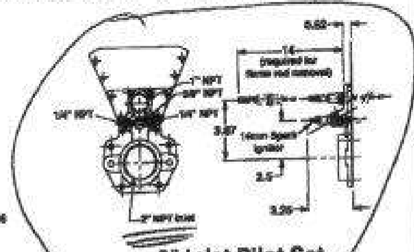
Pilots & end plate assemblies for Series LV-3, -4, & -5 AIRFLO® Burner sections



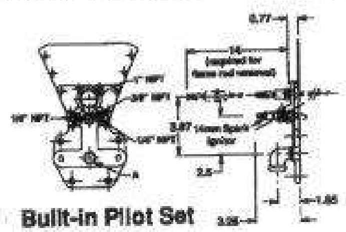
Plain End Plate Set



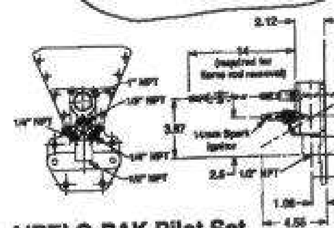
2" End Inlet Set



2" Inlet Pilot Set



Built-in Pilot Set



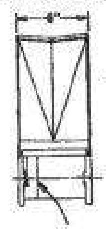
AIRFLO-PAK Pilot Set

Built-in pilot assemblies must mount only where Series "LV" AIRFLO® Burner sections provide for the segmented gas chamber within the burner body casting. See sketches below relative to possible locations for built-in pilot assemblies.

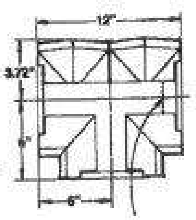
With built-in pilot arrangement, a section of the burner body casting is separated off to form a cavity for pilot gas. Pilot flame emerges through the main burner face.

Pilot mixer options for Series "LV" AIRFLO-PAK pilot sets (above)

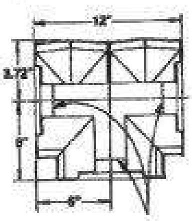
Air-Gas Pilot Mixer – Atmospheric Type



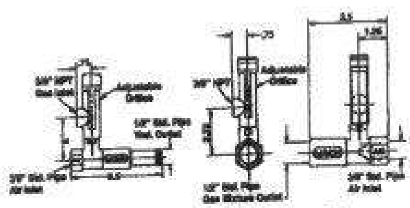
All straight 6" sections, whether gray iron, ductile iron, or aluminum bronze, can accept built-in pilots on **one** end.



Aluminum bronze 12" x 6" tee section can accept built-in pilot only on **right end** of straight 12" side (when viewed from back side of the assembly).



Ductile iron 12" x 6" tee sections can have built-in pilot assembly mounted on any end.
NOTE: Gray iron tee sections do not accept built-in pilot assemblies.



Air-Gas Pilot Mixers – Pressure Type

Terms and Conditions

TERMS OF PAYMENT If High or Good credit rating in latest Dun & Bradstreet reference book, terms will normally be net 30 days from shipment; otherwise, cash in advance.

CANCELLATION/CHANGE Orders may be cancelled or changed only on condition Buyer immediately pays for every loss, cost or damage which seller may suffer as a result. Additional costs associated with Buyer's requested changes, after acceptance of order, may be charged to the Buyer.

QUOTATIONS All quotations expire at noon on the 30th calender day after date of quotation. Unless otherwise stated herein, the prices quoted are firm for acceptance within 30 days of quotation, assuming shipment may be made within a normal 60 day period after day of acceptance by buyer. Should buyer require shipment to be made at a date later than would occur within this normal period or should seller be unable for any other reason beyond its control to ship within said normal period, seller reserves the right to invoice at the prices in effect at time of shipment. Seller reserves the right to correct any proven clerical or stenographic errors.

DELIVERY Every reasonable effort will be made to meet shipment dates stated herein, but seller shall not be responsible for any delay or failure to deliver due to causes beyond its control, including, but not limited to, accidents, casualty, strikes or other labor disputes, acts of God, delays in transportation, government regulations and shortages.

RETURNS No credit will be given for returns except by prior approval of seller at Muncie, Indiana. No special materials or equipment may be returned. No burner nozzle, burner block, or other parts directly exposed to flame, even for short periods, may be returned after use.

SHIPMENTS

Domestic Sales: All prices are F.O.B. Muncie, Indiana and the title to the goods passes to Buyer at that point. Buyer should state method of shipment preferred. Otherwise, seller will use its best judgement. Buyer assumes the risk of damage or loss in transit. If buyer gives a clean receipt for damaged goods or for shipment upon which there are shortages, seller is not responsible.

Export Sales: All unit prices are Ex-Works. Any use of "FOB", "CIF", or other INCOTERMS will apply only to price and not to delivery or passage of title or risk of loss. Delivery of airway bills or other bills of lading before or after the Products arrive in the Territory will not affect the place of delivery or passage of title. The title passes to Buyer at port of entry in the Territory. Buyer shall arrange for shipment and assume risk of damage and loss in transit from its port of entry as designated in the purchase order.

TAXES Buyer shall pay any present or future federal or state tax applicable.

WARRANTY For a period of one year from the date of shipment, seller warrants to buyer the goods manufactured by seller to be free from defects in material and workmanship and to conform with the specifications in seller's current published, technical data, when properly installed, carefully operated and carefully maintained. If within one year from shipment any of the goods fails to so conform, or is found to have been defective in material or workmanship when shipped, and within said period seller receives written notice thereof, such defective goods shall, at seller's option, either be repaired or replaced by seller, F.O.B. Muncie, Indiana, or seller shall refund the purchase price. (The warranty and notice period for Maxon valves shall be one year from installation, but no longer than 18 months from shipment by seller.) In any and all events buyer's remedies shall consist exclusively and solely of those above stated. Seller shall have no liability to buyer for any indirect or consequential damages or injury resulting from any defective or non-conforming goods. **Seller disclaims all other warranties, expressed or implied, including but not limited to any warranty of merchantability or of fitness for use by the buyer or its customers.**

WARNINGS The improper installation or application of the goods; their use with improper wiring, piping, or ventilation; improper system design or engineering; inadequate inspection or testing; the lack of regular careful maintenance of both the goods and any equipment in connection with which the goods are used; the employment of insufficient or unqualified personnel; the lack of careful supervision, proper warnings, operating instructions, and safety precautions; the exposure of the goods to excessive heat, moisture, dust, dirt, corrosion, or any other deleterious condition, each constitutes a hazard which can result in loss of life, serious personal injury, heavy property or business damage, and buyer agrees with seller to itself take and require others to take all reasonable measures to avoid each such hazard. Buyer agrees to notify its customers or users of the product(s), as the case may be, of these warnings, and to deliver to its customers or users of the product(s) all written warnings provided with each product by seller. Additional copies of written warnings are available upon request.

INDEMNITY In the event that any person, firm or corporation asserts any claim against seller arising out of any act or omission of buyer, or arising due to buyer's failure to notify of warnings or deliver warnings as set forth above, and provided that any such claim does not arise out of seller's negligence or any actionable defect in seller's product(s), then in either of such events buyer agrees to indemnify and save seller harmless from and against all liability, loss, cost and expense (including attorney fees) arising out of any such claim.

In the event of any loss, injury or damage, buyer shall not itself, nor permit others to, dismantle, test or examine any of the goods without giving seller sufficient advance notice to be present and allowing such presence.

ENTIRE AGREEMENT No purchase order shall be binding until acknowledged in writing by seller at Muncie, Indiana. Orders, or other documents, submitted by buyer modifying, adding to, or inconsistent with the terms and provisions herein contained, shall be deemed accepted by seller only on the condition that the rights of the parties shall be determined solely by the terms and conditions above set out, and in consummating any such order, seller shall be deemed not to have enlarged, modified, or changed its liabilities or obligations as above set out. This document contains the entire agreement between the parties and supersedes all prior statements of any kind by or between the parties. Acceptance of the goods shall constitute conclusive acceptance of these terms and conditions.

CONTROLLING LAW This proposal and all agreements emanating therefrom shall be controlled by the laws of Indiana. If any provision hereof is deemed or declared to be invalid or unenforceable, all other terms and provisions shall remain in full force and effect.

MAXON CORPORATION

R C Clasby Form 7304 9/03

R. C. CLASBY
Executive Vice President

08-30-2005 07:54 From:ALL-WELD COMPANY LTD 416 299 3387 To:19056320301 P.1/12

ALL-WELD COMPANY LIMITED
Engineers Since 1920

49 PASSMORE AVE., SCARBOROUGH, ONTARIO M1V 4T1
PHONE (416) 299-3311 FAX (416) 299-3387

QUOTATION FAX TRANSMISSION

To: ZETON INC.	Date: AUG29/05	Quotation No. 392-05-C-2	Page 1 of 12
Attention: TROY WONG	Re: 757-20		
Fax: 1-905-632-0301 (3123)	From: TONY GRIST		

We are pleased to submit the following quotation subject to acceptance within 21 days.
Our standard Terms and Conditions would apply to this quote.

PROLOGUE (REVISED AUG29/05).

THIS REVISION IS TO PRESENT FIRM PRICES AS PER YOUR LATEST SPECIFICATION SHEETS AND YOUR DISCUSSIONS WITH VICTOR GIVING THE FINAL HEAT EXCHANGER SPECIFICATION SHEETS THAT WE HAVE SUBMITTED FOR YOUR CHOOSING.
DUE TO THE RAPIDLY FLUCTUATING NICKEL PRICES WE ARE ONLY ABLE TO HONOUR THIS QUOTATION FOR 21 DAYS.

ITEM 1 - HX-1 (REVISED AUG29/05).

TO DESIGNING TO THE ASME CODE FOR 50 PSIG AT 1500°F AND 1/16" CORROSION ALLOWANCE (EXCEPT FOR THE TUBES) ON BOTH SIDES, WITH THE ENGINEERING AGREEMENT THAT THERE CAN BE NO DIFFERENTIAL EXTERNAL PRESSURE ON THE SYSTEM, AND TO YOUR GIVEN PROCESS AS REFLECTED BY OUR HEAT EXCHANGER SPECIFICATION SHEET, PREPARING AND SUBMITTING ELECTRONIC DRAWINGS FOR YOUR APPROVAL, SUPPLYING, FABRICATING, NON-DESTRUCTIVE TESTING INCLUDING SPOT RT, GLASS BEAD BLASTING EXTERNALS, ASME STAMPING, PREPARING FOR SHIPMENT, DELIVERING AND SUPPLYING THE NECESSARY QUALITY CONTROL DOCUMENTATION FOR

1 ONLY ASSEMBLY OF 6 ONLY 6" PIPE SIZE HEAT EXCHANGERS, 2 SHELLS IN PARALLEL AND 3 SHELLS IN SERIES, WITH EACH HAVING 43 ONLY 3/4" OD X .049" WALL X 216" LONG TUBES AS FOLLOWS:

- ALL WETTED MATERIAL WOULD BE TYPE 304H STAINLESS STEEL WHILE REMAINDER WILL BE DUAL GRADE 304/304L
- THE ASSEMBLY WILL BE MOUNTED AS A PACKAGE ON A FRAME TWO VESSELS WIDE BY THREE VESSELS HIGH
- ALLOWANCE FOR 4" X 600# FLANGES INLETS AND OUTLETS AS WELL AS 4 ONLY 3/4" 3000# NPT FITTINGS ON EACH VESSEL

FOR THE SUM OF ....$235,800.00 LOT
nb

continued

G.S.T. and Provincial Sales Taxes Extra unless otherwise specified.

Terms	~~SEE ITEM 6~~
F.O.B.	YOUR PLANT
Delivery	SEE ITEM 5

ALL-WELD COMPANY LIMITED

By: [signature]

FORM 72

ALL-WELD QUOTATION 392-05-G+2.

ITEM 2 - HX-2 (REVISED AUG29/05).

TO DESIGNING TO THE ASME CODE FOR 50 PSIG AT 1500°F AND 1/16" CORROSION ALLOWANCE (EXCEPT FOR THE TUBES) IN THE SHELL AND 50 PSIG FV AT 1300°F AND 1/16" CORROSION ALLOWANCE (EXCEPT THE TUBES) IN THE TUBE SIDE, WITH THE ENGINEERING AGREEMENT THAT THERE CAN BE NO DIFFERENTIAL EXTERNAL PRESSURE ON THE SYSTEM, AND TO YOUR GIVEN PROCESS AS REFLECTED BY OUR HEAT EXCHANGER SPECIFICATION SHEET, PREPARING AND SUBMITTING ELECTRONIC DRAWINGS FOR YOUR APPROVAL, SUPPLYING, FABRICATING, NON-DESTRUCTIVE TESTING INCLUDING SPOT RT, GLASS BEAD BLASTING EXTERNALS, ASME STAMPING, PREPARING FOR SHIPMENT, DELIVERING AND SUPPLYING THE NECESSARY QUALITY CONTROL DOCUMENTATION FOR

1 ONLY ASSEMBLY OF 1 ONLY 6" PIPE SIZE HEAT EXCHANGER HAVING 2 SHELLS WITH THE 27 ONLY 3/4" OD X .049" WALL TUBES IN A 'U' BEND WITH 168" STRAIGHT LENGTHS AS FOLLOWS:

- ALL WETTED MATERIAL WOULD BE TYPE 304H STAINLESS STEEL WHILE REMAINDER WILL BE DUAL GRADE 304/304L

- THE ASSEMBLY WILL BE MOUNTED AS A PACKAGE ON A SINGLE SUPPORT WITH THE TWO VESSELS ONE ABOVE THE OTHER

- ALLOWANCE FOR 2" 600# FLANGES INLETS AND OUTLETS ON THE SHELL SIDE AND 2" 300# ON THE TUBE SIDE AS WELL AS 4 ONLY 3/4" 3000# NPT FITTINGS

FOR THE SUM OF ....$43,600.00 LOT

ITEM 2A - HX-2* (AUG29/05 ADDITION).

TO SUPPLYING 1 ONLY HEAT EXCHANGER AS PER ITEM 2 BUT TO YOUR SELECTION, AS ADVISED TO VICTOR, WITH 27 ONLY TUBES IN LIEU OF 23 AND 12 MORE BAFFLES ON THE SHELL SIDE

FOR THE SUM OF ....$43,200.00 EACH

continued

ALL-WELD QUOTATION 392-05-G+2.

ITEM 3 - HX-3 (REVISED AUG29/05).

TO DESIGNING TO THE ASME CODE FOR 50 PSIG AT 900°F AND 1/16" CORROSION ALLOWANCE (EXCEPT FOR THE TUBES) IN THE SHELL AND 50 PSIG AT 700°F AND 1/16" CORROSION ALLOWANCE (EXCEPT IN THE TUBES) IN THE TUBE SIDE AND TO YOUR GIVEN PROCESS AS REFLECTED BY OUR HEAT EXCHANGER SPECIFICATION SHEET, PREPARING AND SUBMITTING ELECTRONIC DRAWINGS FOR YOUR APPROVAL, SUPPLYING, FABRICATING, NON-DESTRUCTIVE TESTING INCLUDING SPOT RT, GLASS BEAD BLASTING EXTERNALS, ASME STAMPING, PREPARING FOR SHIPMENT, DELIVERING AND SUPPLYING THE NECESSARY QUALITY CONTROL DOCUMENTATION FOR

1 ONLY 6" PIPE SIZE HORIZONTAL HEAT EXCHANGER HAVING 27 ONLY 3/4" OD X .049" WALL TUBES BY 120" STRAIGHT LENGTH AS FOLLOWS:

- MADE ENTIRELY OF TYPE 304/304L STAINLESS STEEL

- ALLOWANCE FOR 1-1/2" X 150# FLANGES INLETS AND OUTLETS ON THE SHELL SIDE AND AN 1-1/2" AND 2" 150# FLANGES ON THE TUBE SIDE AS WELL AS 4 ONLY 3/4" 3000# NPT FITTINGS

FOR THE SUM OF ....$23,500.00 EACH

ITEM 3A - HX-3* (AUG29/05 ADDITION).

TO SUPPLYING 1 ONLY HEAT EXCHANGER AS PER ITEM 3 BUT TO YOUR SELECTION, AS ADVISED TO VICTOR, WITH 27 ONLY TUBES 168" LONG IN LIEU OF 120" LONG AND 13 MORE BAFFLES ON THE SHELL SIDE

FOR THE SUM OF ....$25,100.00 EACH

continued

ALL-WELD QUOTATION 392-05-G+2.

ITEM 4 - HX-4 (AUG29/05 ADDITION).

TO DESIGNING TO THE ASME CODE FOR 70 PSIG AT 350°F AND 1/16" CORROSION ALLOWANCE (EXCEPT FOR THE TUBES) IN THE SHELL AND 50 PSIG AT 800°F AND 1/16" CORROSION ALLOWANCE (EXCEPT IN THE TUBES) IN THE TUBE SIDE AND TO YOUR GIVEN PROCESS AS REFLECTED BY OUR HEAT EXCHANGER SPECIFICATION SHEET, PREPARING AND SUBMITTING ELECTRONIC DRAWINGS FOR YOUR APPROVAL, SUPPLYING, FABRICATING, NON-DESTRUCTIVE TESTING INCLUDING SPOT RT, GLASS BEAD BLASTING EXTERNALS, ASME STAMPING, PREPARING FOR SHIPMENT, DELIVERING AND SUPPLYING THE NECESSARY QUALITY CONTROL DOCUMENTATION FOR

1 ONLY 3" PIPE SIZE HORIZONTAL HEAT EXCHANGER HAVING 7 ONLY 3/4" OD X .049" WALL TUBES BY 60" STRAIGHT LENGTH AS FOLLOWS:

- MADE ENTIRELY OF TYPE 304/304L STAINLESS STEEL

- ALLOWANCE FOR 1/2" X 150# FLANGES INLETS AND OUTLETS ON THE SHELL SIDE AND AN 1-1/2" AND 2" 150# FLANGES ON THE TUBE SIDE AS WELL AS 4 ONLY 3/4" 3000# NPT FITTINGS

FOR THE SUM OF ....$10,900.00 EACH

ITEM 4A - HX-4* (AUG29/05 ADDITION).

TO SUPPLYING 1 ONLY HEAT EXCHANGER AS PER ITEM 4 BUT TO YOUR SELECTION, AS ADVISED TO VICTOR, WITH 7 ONLY TUBES 36" LONG IN LIEU OF 60" LONG AND 12 LESS BAFFLES ON THE SHELL SIDE

FOR THE SUM OF ....$10,600.00 EACH

continued

ALL-WELD QUOTATION 392-05-G+2.

ITEM 5 (AUG29/05 ADDITION).

THE DRAWINGS WOULD BE SUBMITTED OVER A 3 WEEK PERIOD AS READY AND THE VESSELS WOULD BE READY FOR DELIVERY AS COMPLETED AND FULLY WITHIN APPROXIMATELY 16 WEEKS AFTER RECEIPT OF APPROVED DRAWINGS.

ITEM 6 (AUG29/05 ADDITION).

TERMS WOULD BE PROGRESSIVE TO THE FOLLOWING SUGGESTED SCHEDULE:
- 30% ON RECEIPT OF MAJOR MATERIAL OF INDIVIDUAL VESSELS
- 30% ON COMPLETION OF HYDROSTATIC TESTING OF INDIVIDUAL VESSELS
- BALANCE NET 45 DAYS AFTER READY-TO-SHIP DATE OF INDIVIDUAL VESSELS

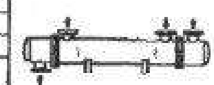
WE WISH ZETON SUCCESS IN 2005,
OUR 85TH ANNIVERSARY YEAR.

AUG-30-2005 07:56 From:ALL-WELD COMPANY LTD 416 299 3387 To:19056320301 P.6/12

HX-1

HEAT EXCHANGER SPECIFICATION SHEET

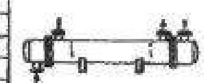
1	Company: ALL-WELD CO.LTD.					
2	Location: Toronto,					
3	Service of Unit: ZETON / AIR COOLER			Our Reference: ALLW1838/O39		
4	Item No.: HX-1			Your Reference:		
5	Date: August 29,2005	Rev No.: 1		Job No.:		
6	Size 7-216	Type BEM hor		Connected in	2 parallel	3 series
7	Surf/unit(eff) 904	ft2; Shells/unit	6	Surf/shell(eff)	151	ft2
8	PERFORMANCE OF ONE UNIT					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		HOT GAS		COLD AIR	
11	Fluid quantity, total	lb/h	3691		3582	
12	Vapor (in/out)	lb/h	3691	3691	3582	3582
13	Liquid	lb/h				
14	Noncondensable	lb/h				
15	Temperature (in/out)	F	1472	325.3	136	1370.2
16	Dew point/bubble point	F				
17	Density	lb/ft3	0.026	0.064	0.224	0.076
18	Viscosity	cp	0.046	0.025	0.021	0.044
19	Molecular weight, vapor					
20	Molecular weight, noncondensable					
21	Specific heat	Btu/(lb*F)	0.286	0.251	0.245	0.278
22	Thermal conductivity	Btu/(ft*h*F)	0.041	0.019	0.016	0.04
23	Latent heat	Btu/lb				
24	Inlet pressure	psia	19.8		51.6	
25	Velocity	ft/s	71.6		65.8	
26	Pressure drop, allow./calc.	psi	4 / 3.575		5 / 0.769	
27	Fouling resist. (min.)	ft2*h*F/Btu	0.002		0.001	
28	Heat exchanged 1134421	Btu/h; MTD (corrected)		131.8		F
29	Transfer rate, service 10	dirty	10	clean	11	Btu/(ft2*h*F)
30	CONSTRUCTION OF ONE SHELL				Sketch	
31			Shell Side	Tube Side		
32	Design/test pressure	psig	50/code	50/code		
33	Design temperature	F	1500	1500		
34	No. passes per shell		1	1		
35	Corrosion allowance	in	0.0	0.0		
36	Connections in	in	4/600	4/600		
37	size/rating out	in	4/600	4/600		
38			/	/		
39	Tube no. 43	od 0.75 ;thk-avg	0.049 in;length	16 ft;pitch	1.0 in	
40	Tube type plain		Material	SS304	Pattern	30
41	Shell SS304 id	od 8.625 in	Shell cover			
42	Channel or bonnet SS304		Channel cover			
43	Tubesheet-stationary SS304		Tubesheet-floating			
44	Floating head cover		Impingement protection		none	
45	Baffle-cross SS304	Type dseg	Cut (%d) 40	h;Spacing: c/c	12.0 in	
46	Baffle-long	Seal type			Inlet	8 in
47	Supports-tube	U-bend		Type		
48	Bypass seal		Tube-tubesheet joint		strength weld	
49	Expansion joint SS304		Type			
50	Rho*V2-Inlet nozzle 1335	Bundle entrance	861	Bundle exit	350	
51	Gaskets-shell side comp. fiber		Tube side	comp. fiber		
52	-floating head					
53	Code requirements ASME Code Sec VIII Div 1			TEMA class	C	
54	Weight/shell 1024	Filled with water	1433	Bundle	409	lb
55	Remarks					
56						
57						
58						



HX-2

HEAT EXCHANGER SPECIFICATION SHEET

1	Company: ALL-WELD CO.LTD.					
2	Location: Toronto,					
3	Service of Unit: ZETON / AIR COOLER		Our Reference: ALLW164/RO.3/07			
4	Item No.: HX-2		Your Reference:			
5	Date: August 29,2005	Rev No.: 1	Job No.:			
6	Size 6-168	Type BEM hor	Connected in	1 parallel	2 series	
7	Surf/unit(eff) 147	ft2; Shells/unit 2	Surf/shell(eff)	73	ft2	
8	PERFORMANCE OF ONE UNIT					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		HOT GAS		COLD AIR	
11	Fluid quantity, total	lb/h	93		725	
12	Vapor (in/out)	lb/h	93	93	725	725
13	Liquid	lb/h				
14	Noncondensable	lb/h				
15	Temperature (in/out)	F	1472	480.6	384.3	1012.8
16	Dew point/bubble point	F				
17	Density	lb/ft3	0.003	0.007	0.112	0.064
18	Viscosity	cp	0.022	0.014	0.028	0.038
19	Molecular weight, vapor					
20	Molecular weight, noncondensable					
21	Specific heat	Btu/(lb*F)	2.829	2.707	0.248	0.267
22	Thermal conductivity	Btu/(ft*h*F)	0.232	0.141	0.021	0.034
23	Latent heat	Btu/lb				
24	Inlet pressure	psia	26.8		35.2	
25	Velocity	ft/s	89.2		50.2	
26	Pressure drop, allow./calc.	psi	2 / 1.019		2.1 / 0.466	
27	Fouling resist. (min.)	ft2*h*F/Btu	0.002		0.001	
28	Heat exchanged 261103	Btu/h; MTD (corrected)	213.5	F		
29	Transfer rate, service 8	dirty 10	clean 10	Btu/(ft2*h*F)		
30	CONSTRUCTION OF ONE SHELL				Sketch	
31			Shell Side	Tube Side		
32	Design/test pressure	psig	50/code	50/code		
33	Design temperature	F	1500	1300		
34	No. passes per shell		1	1		
35	Corrosion allowance	in	0.0	0.0		
36	Connections in	in	2/600	2/300		
37	size/rating out	in	2/600	2/300		
38			/	/		
39	Tube no. 27 od 0.75 ;thk-avg 0.049 in;length 14 ft;pitch 0.9375 in					
40	Tube type plain	Material SS304	Pattern 30			
41	Shell SS304 id od 76.626 in	Shell cover				
42	Channel or bonnet SS304	Channel cover				
43	Tubesheet-stationary SS304	Tubesheet-floating				
44	Floating head cover	Impingement protection none				
45	Baffles-cross SS304 Type sseg	Cut (%d) 40 h;Spacing: c/c 6.0 in				
46	Baffles-long	Seal type	Inlet 6 in			
47	Supports-tube	U-bend	Type			
48	Bypass seal	Tube-tubesheet joint strength weld				
49	Expansion joint SS304	Type				
50	Rho*V2-inlet nozzle 414	Bundle entrance 15	Bundle exit /			
51	Gaskets-shell side comp. fiber	Tube side comp. fiber				
52	-floating head					
53	Code requirements ASME Code Sec VIII Div 1	TEMA class C				
54	Weight/shell 579	Filled with water 755	Bundle 135 lb			
55	Remarks					
56	SHELL SIDE LOAD 261,103 BTU/HR @ SP.HEAT 2.8 BTU/LB,DG.F					
57	TUBE SIDE LOAD 117,436 BTU/HR					
58						

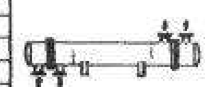


AUG-30-2005 07:57 From:ALL-WELD COMPANY LTD 416 299 3387 To:19056320301 P.8/12

Hx-2

HEAT EXCHANGER SPECIFICATION SHEET

1	Company: ALL-WELD CO.LTD.					
2	Location: Toronto,					
3	Service of Unit: ZETON / AIR COOLER			Our Reference: ALLW164A/Q382		
4	Item No.: HX-2			Your Reference:		
5	Date: August 29.2005	Rev No.: 1		Job No.:		
6	Size 6-168	Type BEM hor		Connected in	1 parallel	1 series
7	Surf/unit(eff) 63	ft2; Shells/unit 1		Surf/shell(eff)	63	ft2
8	PERFORMANCE OF ONE UNIT					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		HOT GAS		COLD AIR	
11	Fluid quantity, total	lb/h	93		725	
12	Vapor (in/out)	lb/h	93	93	725	725
13	Liquid	lb/h				
14	Noncondensable	lb/h				
15	Temperature (in/out)	F	1472	480.8	384.3	1012.8
16	Dew point/bubble point	F				
17	Density	lb/ft3	0.008	0.018	0.112	0.064
18	Viscosity	cp	0.039	0.017	0.025	0.036
19	Molecular weight, vapor					
20	Molecular weight, noncondensable					
21	Specific heat	Btu/(lb*F)	1.283	1.188	0.248	0.267
22	Thermal conductivity	Btu/(ft*h*F)	0.192	0.105	0.021	0.034
23	Latent heat	Btu/lb				
24	Inlet pressure	psia	26.8		35.2	
25	Velocity	ft/s	47.7		59.0	
26	Pressure drop, allow./calc.	psi	2 / 0.468		2.1 / 0.786	
27	Fouling resist. (min.)	ft2*h*F/Btu	0.002		0.001	
28	Heat exchanged 117436	Btu/h; MTD (corrected)		213.5		F
29	Transfer rate, service 8	dirty	10	clean	11	Btu/(ft2*h*F)
30	CONSTRUCTION OF ONE SHELL				Sketch	
31			Shell Side	Tube Side		
32	Design/test pressure	psig	50/code	50/code		
33	Design temperature	F	1500	1300		
34	No. passes per shell		1	1		
35	Corrosion allowance	in	0.0	0.0		
36	Connections in	in	2/300	2/300		
37	size/rating out	in	2/300	2/300		
38			/	/		
39	Tube no. 23 od 0.75	thk-avg 0.049 in; length 14 ft; pitch 0.9375 in				
40	Tube type plain	Material SS304		Pattern 30		
41	Shell SS304 id od 8.625 in	Shell cover				
42	Channel or bonnet SS304	Channel cover				
43	Tubesheet-stationary SS304	Tubesheet-floating				
44	Floating head cover	Impingement protection none				
45	Baffles-cross SS304 Type sseg	Cut (%d) 40 h; Spacing: c/c 4.0 in				
46	Baffles-long	Seal type		Inlet 6 in		
47	Supports-tube	U-bend		Type		
48	Bypass seal	Tube-tubesheet joint strength weld				
49	Expansion joint SS304	Type				
50	RhoV2-inlet nozzle 172	Bundle entrance 6		Bundle exit 7		
51	Gaskets-shell side comp. fiber	Tube side comp. fiber				
52	-floating head					
53	Code requirements ASME Code Sec VIII Div 1			TEMA class C		
54	Weight/shell 588	Filled with water 744		Bundle 183		lb
55	Remarks					
56	SHELL SIDE LOAD 114,884 BTU/HR @ SP.HEAT 1.283 BTU/LB.DG.F					
57	TUBE SIDE LOAD 117,436 BTU/HR					
58						

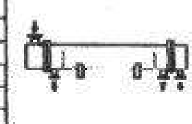


AUG-30-2005 07:58 From:ALL-WELD COMPANY LTD 416 299 3387 To:19056320301 P.9/12

HX-3

HEAT EXCHANGER SPECIFICATION SHEET

1	Company: ALL-WELD CO.LTD.						
2	Location: Toronto,						
3	Service of Unit: ZETON / AIR HEATER				Our Reference: ALLW1628PO392		
4	Item No.: HX-3				Your Reference:		
5	Date: August 29,2005		Rev No.: 1		Job No.:		
6	Size: 6-120		Type BEM hor		Connected in	1 parallel	2 series
7	Surf/unit(eff)	105	ft2; Shells/unit	2	Surf/shell(eff)	52	ft2
8	PERFORMANCE OF ONE UNIT						
9	Fluid allocation			Shell Side		Tube Side	
10	Fluid name			AIR		HOT GAS	
11	Fluid quantity, total		lb/h	725		93	
12	Vapor (in/out)		lb/h	725	725	93	93
13	Liquid		lb/h				
14	Noncondensable		lb/h				
15	Temperature (in/out)		F	168	501.3	785	214.8
16	Dew point/bubble point		F				
17	Density		lb/ft3	0.167	0.108	0.004	0.007
18	Viscosity		cp	0.021	0.029	0.017	0.01
19	Molecular weight, vapor						
20	Molecular weight, noncondensable						
21	Specific heat		Btu/(lb*F)	0.244	0.251	2.713	2.611
22	Thermal conductivity		Btu/(ft*h*F)	0.016	0.023	0.169	0.115
23	Latent heat		Btu/lb				
24	Inlet pressure		psia	38.8		20.2	
25	Velocity		ft/s	20.7		102.3	
26	Pressure drop, allow./calc.		psi	2 / 1.738		2 / 0.156	
27	Fouling resist. (min.)		ft2*h*F/Btu	0.001		0.002	
28	Heat exchanged	142327	Btu/h; MTD (corrected)		142.0		F
29	Transfer rate, service	10	dirty	10	clean	11	Btu/(ft2*h*F)
30	CONSTRUCTION OF ONE SHELL					Sketch	
31				Shell Side	Tube Side		
32	Design/test pressure		psig	50/code	50/code		
33	Design temperature		F	900	700		
34	No. passes per shell			1	1		
35	Corrosion allowance		in	0.0	0.0		
36	Connections	In	in	1.5/150	2/150		
37	size/rating	out	in	1.5/150	1.5/150		
38				/	/		
39	Tube no. 27	od 0.75	thk-avg 0.049 in;length	10 ft;pitch	0.9375 in		
40	Tube type plain			Material SS304		Pattern 30	
41	Shell SS304	id	od 6.625 in	Shell cover			
42	Channel or bonnet	SS304		Channel cover			
43	Tubesheet-stationary	SS304		Tubesheet-floating			
44	Floating head cover			Impingement protection		none	
45	Baffles-cross	SS304	Type sseg	Cut (%d) 30	h;Spacing: c/c	6.0 in	
46	Baffles-long		Seal type			Inlet	4 in
47	Supports-tube		U-bend		Type		
48	Bypass seal			Tube-tubesheet joint		strength weld	
49	Expansion joint	SS304		Type			
50	Rho*V2-Inlet nozzle	1811	Bundle entrance	121	Bundle exit	189	
51	Gaskets-shell side	comp. fiber		Tube side	comp. fiber		
52	-floating head						
53	Code requirements	ASME Code Sec VIII Div 1			TEMA class	C	
54	Weight/shell	395	Filled with water	531	Bundle	137	lb
55	Remarks						
56	TUBE SIDE LOAD 142,327 BTU/HR, SP. HEAT 2.713/2.611						
57	SHELL SIDE LOAD 81,715 BTU/HR						
58	LOADS LEFT UNBALLANCED						

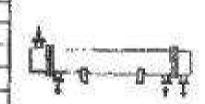


AUG-30-2005 07:58 From:ALL-WELD COMPANY LTD 416 299 3387 To:19056320301 P.10/12

HX-3

HEAT EXCHANGER SPECIFICATION SHEET

1	Company: ALL-WELD CO LTD					
2	Location: Toronto,					
3	Service of Unit: ZETON / AIR HEATER			Our Reference: ALLW162A/Q392		
4	Item No.: HX-3			Your Reference:		
5	Date: August 29,2005	Rev No.: 1		Job No.:		
6	Size 6-168	Type BEM hor		Connected in	1 parallel	1 series
7	Surf/unit(eff) 73	ft2; Shells/unit 1		Surf/shell(eff)	73	ft2
8	PERFORMANCE OF ONE UNIT					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		AIR		HOT GAS	
11	Fluid quantity, total	lb/h	725		93	
12	Vapor (in/out)	lb/h	725	725	93	93
13	Liquid	lb/h				
14	Noncondensable	lb/h				
15	Temperature (in/out)	F	158	501.5	786	214.9
16	Dew point/bubble point	F				
17	Density	lb/ft3	0.107	0.108	0.01	0.016
18	Viscosity	cp	0.021	0.029	0.022	0.012
19	Molecular weight, vapor					
20	Molecular weight, noncondensable					
21	Specific heat	Btu/(lb*F)	0.244	0.251	1.191	1.132
22	Thermal conductivity	Btu/(ft*h*F)	0.016	0.023	0.124	0.076
23	Latent heat	Btu/lb				
24	Inlet pressure	psia	38.6		20.2	
25	Velocity	ft/s	20.7		42.7	
26	Pressure drop, allow./calc.	psi	2 / 1.058		2 / 0.037	
27	Fouling resist. (min.)	ft2*h*F/Btu	0.001		0.002	
28	Heat exchanged 62108	Btu/h; MTD (corrected)		142.0		F
29	Transfer rate, service 6	dirty 7		clean 7		Btu/(ft2*h*F)
30	CONSTRUCTION OF ONE SHELL				Sketch	
31			Shell Side	Tube Side		
32	Design/test pressure	psig	50/code	80/code		
33	Design temperature	F	900	700		
34	No. passes per shell		1	1		
35	Corrosion allowance	in	0.0	0.0		
36	Connections in	in	1.5/150	2/150		
37	size/rating out	in	1.5/150	1.5/150		
38				/		
39	Tube no.: 27	od 0.75 ; thk-avg 0.049	in; length	14 ft; pitch	0.9375 in	
40	Tube type: plain		Material	SS304	Pattern	30
41	Shell SS304	id od 6.625 in	Shell cover			
42	Channel or bonnet	SS304	Channel cover			
43	Tubesheet-stationary	SS304	Tubesheet-floating			
44	Floating head cover		Impingement protection		none	
45	Baffles-cross SS304	Type sseg	Cut (%d) 30	h; Spacing: c/c	6.0 in	
46	Baffles-long	Seal type			Inlet	4 in
47	Supports-tube	U-bend		Type		
48	Bypass seal		Tube-tubesheet joint		strength weld	
49	Expansion joint	SS304	Type			
50	Rho*V2-Inlet nozzle 1611	Bundle entrance	121	Bundle exit	189	
51	Gaskets-shell side	comp. fiber	Tube side	comp. fiber		
52	-floating head					
53	Code requirements	ASME Code Sec VIII Div 1		TEMA class	C	
54	Weight/shell 477	Filled with water	682	Bundle	183	lb
55	Remarks					
56	TUBE SIDE THERMAL PROPERTIES AS PER ZETON SPEC'S					
57						
58						

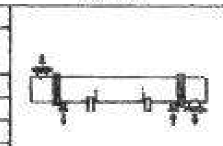


AUG-30-2005 07:59 From:ALL-WELD COMPANY LTD 416 299 3387 To:19056320301 P.11/12

HX-4

HEAT EXCHANGER SPECIFICATION SHEET

1	Company: ALL-WELD CO.LTD.					
2	Location: Toronto,					
3	Service of Unit: ZETON / AIR HEATER		Our Reference:ALLW166/Q392			
4	Item No.: HX-4		Your Reference:			
5	Date: August 29,2005	Rev No.: 1	Job No.:			
6	Size 3-60	Type BEM hor	Connected in	1 parallel	1 series	
7	Surf/unit(eff) 7	ft2; Shells/unit 1	Surf/shell(eff) 7	ft2		
8	PERFORMANCE OF ONE UNIT					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		WATER		HOT GAS	
11	Fluid quantity, total	lb/h	73		93	
12	Vapor (in/out)	lb/h			93	93
13	Liquid	lb/h	73	73		
14	Noncondensable	lb/h				
15	Temperature (in/out)	F	110	277.5	725.3	482
16	Dew point/bubble point	F				
17	Density	lb/ft3	62.008	57.976	0.085	0.108
18	Viscosity	cp	0.615	0.215	0.018	0.014
19	Molecular weight, vapor					
20	Molecular weight, noncondensable					
21	Specific heat	Btu/(lb*F)	1	1.008	2.747	2.711
22	Thermal conductivity	Btu/(ft*h*F)	0.361	0.369	0.164	0.143
23	Latent heat	Btu/lb				
24	Inlet pressure	psia	42.6		24.7	
25	Velocity	ft/s	0.0		311.7	
26	Pressure drop, allow./calc.	psi	2 / 0.001		2 / 0.221	
27	Fouling resist. (min.)	ft2*h*F/Btu	0.001		0.002	
28	Heat exchanged 61947	Btu/h; MTD (corrected)	408.7	F		
29	Transfer rate, service 23	dirty 46	clean 54	Btu/(ft2*h*F)		
30	CONSTRUCTION OF ONE SHELL				Sketch	
31			Shell Side	Tube Side		
32	Design/test pressure	psig	70/code	30/code		
33	Design temperature	F	350	800		
34	No. passes per shell		1	1		
35	Corrosion allowance	in	0.0	0.0		
36	Connections in	in	0.5/150	1.5/150		
37	size/rating out	in	0.5/150	2/150		
38						
39	Tube no. 7 od 0.75 ;thk-avg 0.049 in;length 5 ft;pitch 0.9375 in					
40	Tube type plain		Material SS304		Pattern 30	
41	Shell SS304 id od 3.5 in		Shell cover			
42	Channel or bonnet SS304		Channel cover			
43	Tubesheet-stationary SS304		Tubesheet-floating			
44	Floating head cover		Impingement protection none			
45	Baffles-cross SS304 Type sseg		Cut (%d) 20 h;Spacing: c/c 2.0 in			
46	Baffles-long	Seal type			Inlet 4 in	
47	Supports-tube	U-bend	Type			
48	Bypass seal		Tube-tubesheet joint	strength weld		
49	Expansion joint SS304		Type			
50	Rho*V2-inlet nozzle 4	Bundle entrance 0	Bundle exit 0			
51	Gaskets-shell side comp. fiber		Tube side comp. fiber			
52	-floating head					
53	Code requirements ASME Code Sec VIII Div 1		TEMA class C			
54	Weight/shell 185	Filled with water 203	Bundle 21	lb		
55	Remarks					
56	TUBE SIDE LOAD 61,947 BTU/HR					
57	SHELL SIDE LOAD 12,224 BTU/HR					
58	LOADS LEFT UNBALANCED					

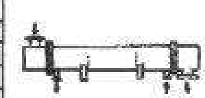


AUG-30-2005 07:52 From:ALL-WELD COMPANY LTD 416 299 3387 To:19056320301 P.12/12

HX-4

HEAT EXCHANGER SPECIFICATION SHEET

1	Company: ALL-WELD CO.LTD.					
2	Location: Toronto,					
3	Service of Unit: ZETON / AIR HEATER				Our Reference: ALLW165A/Q302	
4	Item No.: HX-4				Your Reference:	
5	Date: August 28,2005	Rev No.: 1			Job No.:	
6	Size 3-36	Type BEM hor	Connected in		1 parallel	1 series
7	Surf/unit(eff) 4	ft2; Shells/unit 1	Surf/shell(eff)		4	ft2
8	PERFORMANCE OF ONE UNIT					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		WATER		HOT GAS	
11	Fluid quantity, total	lb/h	73		93	
12	Vapor (in/out)	lb/h			93	93
13	Liquid	lb/h	73	73		
14	Noncondensable	lb/h				
15	Temperature (in/out)	F	110	277.5	725.3	482
16	Dew point/bubble point	F				
17	Density	lb/ft3	62.008	57.979	0.012	0.014
18	Viscosity	cp	0.615	0.215	0.021	0.017
19	Molecular weight, vapor					
20	Molecular weight, noncondensable					
21	Specific heat	Btu/(lb*F)	1	1.009	1.193	1.17
22	Thermal conductivity	Btu/(ft*h*F)	0.361	0.389	0.131	0.107
23	Latent heat	Btu/lb				
24	Inlet pressure	psia	42.5		24.7	
25	Velocity	ft/s	0.0		128.8	
26	Pressure drop, allow./calc.	psi	2 / 0.001		2 / 0.076	
27	Fouling resist. (min.)	ft2*h*F/Btu	0.001		0.002	
28	Heat exchanged 28820	Btu/h; MTD (corrected)		408.7		F
29	Transfer rate, service 17	dirty	30	clean	33	Btu/(ft2*h*F)
30	CONSTRUCTION OF ONE SHELL				Sketch	
31			Shell Side	Tube Side		
32	Design/test pressure	psig	70/code	50/code		
33	Design temperature	F	350	800		
34	No. passes per shell		1	1		
35	Corrosion allowance	in	0.0	0.0		
36	Connections in	in	0.5/150	1.5/150		
37	size/rating out	in	0.5/150	2/150		
38			/	/		
39	Tube no. 7 od 0.75 ;thk-avg	0.049 in;length		3 ft;pitch	0.9375 in	
40	Tube type plain		Material SS304		Pattern	30
41	Shell SS304 id od 3.5 in		Shell cover			
42	Channel or bonnet SS304		Channel cover			
43	Tubesheet-stationary SS304		Tubesheet-floating			
44	Floating head cover		Impingement protection		none	
45	Baffles-cross SS304 Type sseg		Cut (%d) 20	h;Spacing: c/c	2.0 in	
46	Baffles-long	Seal type			Inlet	4 in
47	Supports-tube	U-bend		Type		
48	Bypass seal		Tube-tubesheet joint		strength weld	
49	Expansion joint SS304		Type			
50	Rho*V2-inlet nozzle 4	Bundle entrance	0		Bundle exit	0
51	Gaskets-shell side comp. fiber		Tube side	comp. fiber		
52	-floating head					
53	Code requirements ASME Code Sec VIII Div 1				TEMA class	C
54	Weight/shell 174	Filled with water	186		Bundle 16	lb
55	Remarks					
56	TUBE SIDE LOAD 28,820 BTU/HR					
57	SHELL SIDE LOAD 12,224 BTU/HR					
58	LOADS LEFT UNBALANCED					



RHI

RHI Canada Inc.
4355 Fairview Street
Burlington, Ontario L7L 2A4
Phone: (905) 639-8660
Fax: (905) 639-5357

August 31, 2005

Zeton Inc.
740 Oval Court
Burlington, Ontario
L7L 6A9

Attention: Mr. Richard Zhu

Reference: Reactor Lining
RHI Canada Ref. BC05-118

Gentlemen:

We are pleased to submit our revised contract proposal to perform the refractory lining of the Zeton Reactor at our Burlington, Ontario facility.

Our proposal is based on:

- Information provided via email.
- The Zeton Inc. reference drawing 757-20 Rev. B
- The terms and conditions of this proposal.

We thank you for this opportunity to quote on your requirements, and look forward to being of service to you in the near future.

Yours truly,
RHI Canada Inc.

Jeff Beaudoin
Estimator

Scope of Work

RHI Canada will supply and install the necessary materials to line one (1) Zeton Reactor at our Burlington Ontario facility, as described below.

REFRACTORY LINING – Ceramic Insulation Back-up

Zeton Reactor: 50" I.D.

- Supply and install 7-1/2"of **Plivaform Board Insulation**, as the back up Layer of refractory.
- Supply and install 6" of Comprit 94 CD, as the hot-face layer of castable.
- The three (3) Thermowells (T1, T2, and T3) are cast with 4" of Comprit 94 CD Castable complete with a 1/8" 970 J Ceramic paper backing.
- The two (2) transition pieces (GI, GO) are cast with 4" of Comprit 94 CD Castable complete with a 1/8" 970 J Ceramic paper backing.
- The Arched Catalyst Support is cast with 12" of Comprit 94 CD Castable, complete with approx. 56 1-1/2" holes for ventilation purposes.
- Refractory lining dried out by RHI Canada at 650 °F in our onsite kiln.

Anchoring: Refractory lining secured with SS304 295 mm RA anchors, in accordance with RHI Canada engineering standards.

PRICING

Refractory Lining – Caramic Insulation Back-up

Zeton Reactor: 50" I.D.

Our firm price to perform the scope of work as described above is: **$ 43, 726**

Our pricing is:
F.O.B. Burlington, Ontario.
GST and PST extra, if applicable.
Valid until December 31, 2005.
Payment terms are net 30 days after date of invoice.
Please allow 1 - 2 weeks delivery upon receipt of order.

Agreement will be a purchase order issued in reference to this proposal in its entirety.

Items by RHI Canada

The following items are included in our pricing as part of this proposal.

1. Supply and dumping of debris containers for refractory rubble and debris generated by this Contractor.
2. Loading, unloading and handling of our materials and equipment on the work site.
3. Supply of Forklift for the duration of the job.
4. Welding equipment, and manpower.
5. All freight related to this proposal.
6. Bake-out of refractory lined reactor.

Items by Purchaser

It is understood that the Purchaser will supply the following:

1. All steel fabrication, and installation of any steel work.

Conditions

The following conditions of sale constitute the basis on which this proposal is made.

Supervision: This proposal includes the services of a RHI Canada foreman, fully experienced in all facets of the refractory industry throughout the duration of this project.

Hours of Work: This proposal is based on performing the work on a 1 x 8 hour shift per day option shift basis as. It does not provide for any work on Saturdays, Sundays or Holidays. Any additional overtime, meal allowance, or shift premiums made at the Purchaser's request to expedite this work will be charged as an extra to the contract price.

Labour Availability: This proposal is based on the availability of labour from local unions. Should labour from other localities be required, all travel and maintenance costs for this labour will be extra to contract.

Hazardous Materials: In the event that this contract entails the handling, use, installation or demolition by RHI Canada personnel of hazardous materials provided by, or that are a part of the Purchaser's equipment, the Purchaser will provide appropriate Material Safety Data Sheets on any such materials. The MSDS will identify and make known the material, ingredients, physical data, fire and explosion hazard, health hazard, reactivity, spill or leak procedures, special protection requirements and special precautions. The MSDS are to be signed by an agent of the Purchaser and are to be provided to the responsible RHI Canada representative.
Handling, registration and disposal of all hazardous materials (ie: asbestos or chrome-based refractory products) shall be the responsibility of the Owner of said materials in accordance with Provincial and/or Federal Legislation.

Interference: If the Purchaser or his appointed agents or representatives, interfere with the continuous work of RHI Canada or its subcontractors, causing delay, payment shall be made by the Purchaser to cover all costs incurred by the said work stoppage.

Specifications: This proposal does not include or cover any specifications, drawings or procedures, which are not stated herein.
Any additional costs incurred as a result of specifications, drawings or procedures issued after the date of this proposal, are to be an extra to the contract price.

Metal Preparation: It is understood that the Purchaser will supply manpower and equipment for steel fabrication, surface preparation, welding of anchors or exterior refinishing as may be required.

Contract: No representations or understandings shall be binding unless included in this contract proposal. It is expressly understood that the Contractor assumes no consequential loss under this contract.

Uncontrollable Influences: If, for any reason beyond the seller's control, as for example by failure of its suppliers to make delivery of the merchandise in accordance with the terms of the order, strikes, embargoes, present or future Government regulations, Acts of God, etc., the seller will be released from liability from any resulting incomplete fulfilment of the order, and any extraordinary expenses involved in connection with delivery of the merchandise will be for the buyer's account.

Insurance: We agree to furnish such insurance as is necessary to cover any possible claims under the Workmen's Compensation Act, or any other claims resulting from personal injury or property damage, which might result from operation under this agreement.

Invoicing: Progress billings and/or final billings will be forwarded to the Purchaser's office for invoice approval and payment unless otherwise stipulated on the purchase order.
Progress billings may be issued for all labour and materials expended during the performance of the project.

Acceptance: Upon completion of the scope of work detailed herein, the Owner/Engineer will inspect the subject scope of work to ensure all work has been completed to the satisfaction of the Owner/Engineer. The Owner/Engineer will be required to sign an "Acceptance" form thereby signifying the work has been completed in accordance with the contract terms and conditions.
Acknowledgement of the aforementioned acceptance will not relieve RHI Canada of its guarantee or contractual obligations stipulated in this contract.

Terms of Payment: Net 30 days. Progress billings shall be payable 30 days from date of invoice, subject to holdback conditions. From the date of acceptance, all accumulated holdbacks shall be payable in accordance with provincial legislation authorized in the Mechanics Lien Act or other Bills covering contract holdback.

Garbage Containers: Supply free issue within fifty feet of the designated work area. Demurrage, dumping, removal, etc. will be by others.

Independent Testing: Costs for independent testing of our refractory products are not included in this proposal and are available upon request.

Guarantee: It is implicitly understood that the Contractor shall not be liable for any loss and/or damages incurred by the Purchaser or user as a result of installation accomplished pursuant to the attached proposal, except as follows:
We guarantee and warrant that all installation work provided under this contract is free from installation defects. If any installation supplied by the Contractor is found to be defective, the Contractor agrees to provide sufficient installation and/or material to correct the deficiency provided the Purchaser notifies the Contractor in writing of such defect no later than one (1) year from date of installation completion. This guarantee does not extend to normal wear and tear of materials and/or equipment or to damages caused by abnormal service conditions that are not brought to the attention of the Contractor in writing at the time the attached proposal is requested.
The Purchaser shall give prompt notice to the Contractor of any observed defects. The Contractor shall not be liable for back charges incidental to field changes or correction of workmanship performed hereunder unless ample opportunity is given to the Contractor to inspect the workmanship claimed to be defective, and then only after the field changes or corrections have been authorized in writing by the Contractor.
Should warranty work be performed by RHI Canada Inc., all such work shall be undertaken on the basis of working a regular eight-hour shift on a Monday through Friday basis exclusive of statutory holidays.
It is to be understood that all equipment and/or materials, apart from those manufactured by RHI Canada Inc., bear only the original manufacturer's or supplier's guarantee, warranty and subsequent service.

Consequential Loss: Notwithstanding anything contained in the Contract/Proposal Documents the Contractor shall not in any case be liable for any special, indirect or consequential damages including without limitation, damages for lost profits, lost business, lost savings or other economic or business loss or claims of any kind or nature, whatsoever.

Your reference: Screw compressor
Our reference: ON-8164a
23/Aug/05

SCOPE OF SUPPLY

1 AERZEN DELTA SCREW COMPRESSOR VM 21R including:

1 AERZEN VM 21 oil free screw compressor with integrated step-up gearbox (i8)
1 Toshiba EQPIII, 150hp, 3600rpm, 460V/3/60, TEFC, Premium Efficiency, SF=1.15
1 Integrated forced oil supply system c/w oil demister pump*, oil pressure regulator, filter, and air to oil cooler
* NOTE - Oil pump is driven by a 0.5-hp motor (1-phase, 120V or 460V voltage to be confirmed by client)
1 Structural steel base frame with flexible machine mountings
1 Two stage inlet filter (centrifugal separation, followed by fine filter)
1 Inlet silencing conduit
1 Discharge silencing chamber
1 Full flow pressure relief valve preset to 50-psig
1 Full bore check valve
1 Stainless steel expansion joint for discharge connection of 3" 150#
1 Fully balanced V-belt drive with auto-tensioning system
1 Instrument panel with indication and switches for inlet pressure (filter), discharge pressure, and oil pressure

Instrumentation
Inlet and discharge pressure switch, discharge pressure gauge, oil pressure switch, oil pressure gauge, discharge thermometer, oil thermometer

OPTIONAL
1 Acoustic hood mounted on a structural skid, ventilated by electrical fan, executed as an oil drip pan - **OUTDOOR DESIGN**

Tests and measurements:
1 1.5 hour flow test at the factory (Germany) on a calibrated test bed, at maximum operating conditions and according to DIN 1945. acceptance tolerance: +/- 5%.
A complete test report will be provided

Your reference: Screw compressor
Our reference: ON-8164a
23/Aug/05

PERFORMANCE DATA:

VM 21R Delta Screw Compressor Package

Conditions		Design Max Flow	Design Min Flow	Turndown 1 Minimum
Flow at **inlet** conditions	m3/hr	1420	619	287
	m3/min	23.7	10.3	4.8
	icfm	836	364	169
Inlet pressure (abs.)	bar	1.01	1.01	1.01
	Psi	14.69	14.69	14.69
Pressure differential	bar g	2.96	2.96	1.96
	Psig	42.9	42.9	28.4
Inlet temperature	°C	40	40	40
	°F	104	104	104
Discharge temperature	°C	241	250	229
Compressor speed	RPM	20,762	10,395	**6,100**
Motor Speed	RPM	3560	1782	1046
Power required at shaft	Kw	106.00	45.70	19.30
	HP	142.15	61.28	25.88
Motor rating	HP	150		
Noise level without acoustic hood	dB(A)	102		
Noise level with acoustic hood	dB(A)	85		
Tolerances according to DIN 1945:				
Flow at inlet conditions	+/- 5%			
Power required at shaft	+/- 5%			

Blower package noise level:

Free field measurement at 1m from the complete blower package (tolerance +/- 2 dB(A))

Your reference: Screw compressor
Our reference: ON-8164a
23/Aug/05

TERMS AND CONDITIONS

		Unit Price	Extended Price
	PRICE:	**43,825.00 $**	**43,825.00 $**
Turndown 2 Minimum	**Option: Outdoor Acoustic Enclosure adder:**	**9,625.00 $**	**9,625.00 $**

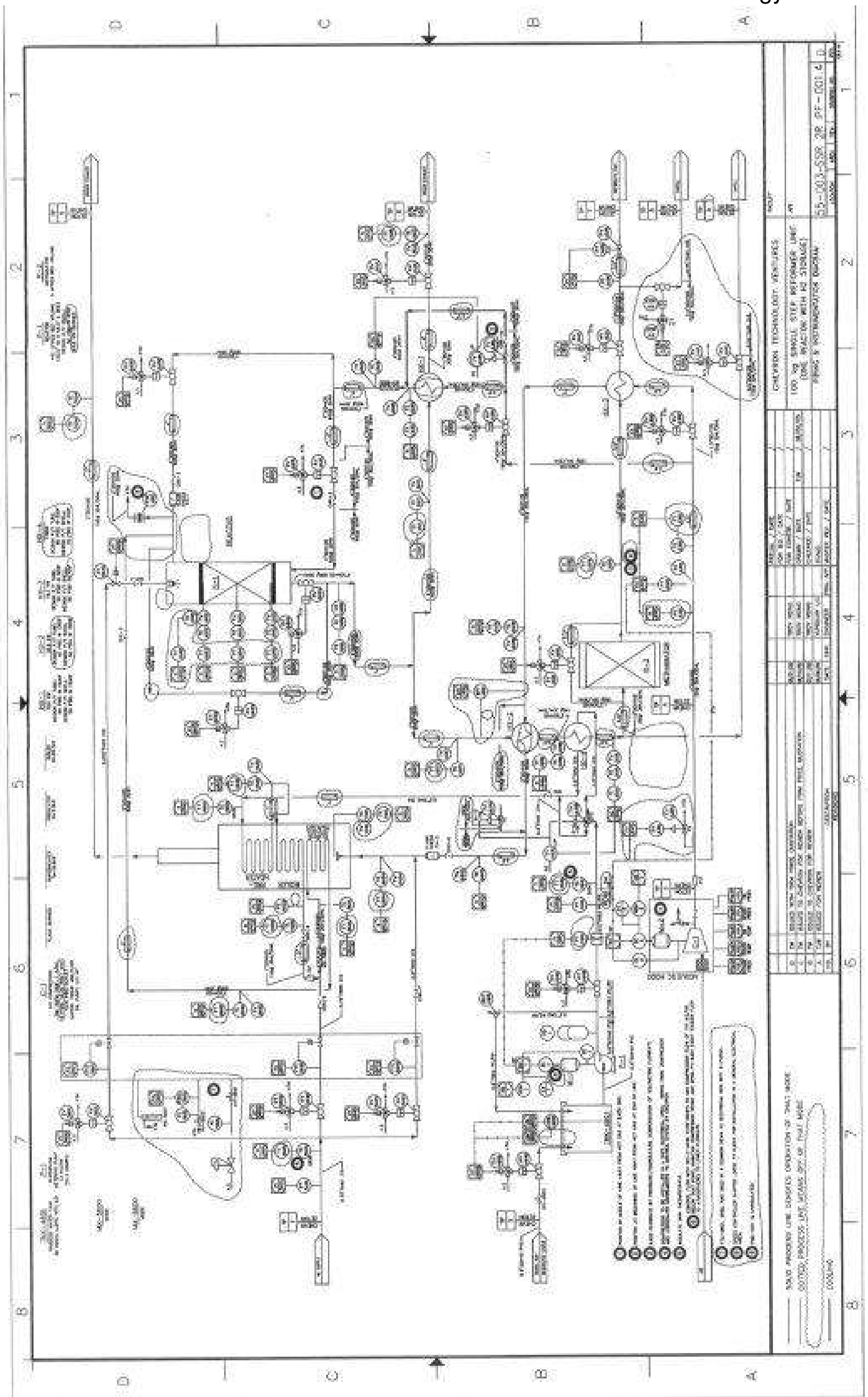
332	**Funds:**	Canadian dollars
5.5		
195	**Payment terms:**	Net 30 days
1.01	**Prices firm until:**	90 days
14.69		
	Taxes:	Extra
0.70		
10.2	**Packing:**	Included
40	**F.O.B.:**	Vaudreuil, Quebec
104		
	Warranty:	12 months following commissioning, or 18 months from delivery, whichever occurs first
128		
6,100	**Delivery:**	18 weeks (with or without acoustic hood)
1046		

10.40
13.95

- To avoid warranty conflicts, we recommend that our start-up services be ordered and the inspection & operation procedures in our manual be respected.
- The goods remain our property until full payment.
- Past due invoice amounts carry an interest charge at prevailing commercial lending rates.
- Extended payment delays may void the warranty.

1 Unit
1 Unit

APPENDIX N



APPENDIX O

QUOTATION

100 KG PER DAY SINGLE STEP REFORMER (SSR) UNIT

Quotation No. 757-20A

Prepared for:

Chevron Technology Ventures

by

Zeton Inc.

September 1, 2005

QUOTATION

Note: All Prices are quoted in US DOLLARS, local taxes and duties not included.

1. Quotation

1.1 Price, SSR Unit (+/- 10%)
F.O.B, ZETON Inc., BURLINGTON, CANADA **US $1,780,000.00**

The above quotation is for the SSR Unit based the following:

- P&ID 55-003-SSR 2R PF-001.4 Rev D
- Exchanger Design Cases Rev 5
- Reforming Air Pressure Drop, Rev 3
- Regeneration Air Pressure Drop, Rev 3
- Steam NG Pressure Drop, Rev 1
- Zeton's attached Scope of Work and specifications
- Chevron specifications PVM-EG-4748-B AND EXH-EG-4764

This price excludes the Preheater/Boiler/Superheater package, and the control system. The price includes detailed engineering, procurement, manufacturing/fabrication, factory testing at Zeton's facility and documentation, as set out herein.

The guestimated price for the Preheater/Boiler/Superheater is **US$265,000**. We can follow with a quotation for this equipment when requested. Based upon our search so far, this is probably a custom designed piece of equipment, and therefore some time will be required to finalize the price.

The price used for exchangers HX-1, HX-2, and HX-3 included in this quotation is **US$260,000** total for the three units. The only alternate price for these three exchangers that Zeton received was **US$920,000**. Zeton have used the **US$260,000** exchanger supplier for many years and are confident in their abilities. However, there is a huge financial risk if the exchangers actually end up costing **US$920,000** upon detailed design. Rather than add a huge contingency to cover this situation, any additional costs for HX-1, HX-2 and HX-3 above **US$260,000** will be a change in scope, and will be charged to the client. Based upon Zeton's previous experience with this exchanger supplier, we believe that the chances of there being any additional costs are low.

2. Installation

It is expected that the client will install the skid and connect all utilities and feeds to the tie-in points at the skid edge. If required, Zeton will provide assistance for installation.

The cost for this service will be charged at the following labor rates for time spent at the customer's site plus travel and living expenses. These rates are based on installation taking place in 2005.

Project Engineer	US$ 93.00/hr
Control System Engineer	US$ 93.00/hr
Electrical Engineer	US$ 90.00/hr
Mechanical Technician	US$ 75.00/hr
Electrical Technician	US$ 75.00/hr

3. Delivery Schedule:

Schedule is attached. P&ID and vessel specification review is to be within five working days of submittal to meet schedule.

4. Documentation

4.1 Documentation for Approval Review

Documentation for approval review (1 set) will be as follows. This documentation will be sent to the client for approval as it becomes available. Only minor changes (small changes to process conditions, calibration, nozzle locations, and minor modifications to piping/equipment layout) have been allowed for within the scope of this price. Any valves, instruments, or equipment added to the P&ID will be at additional cost.

- P&ID's
- Process bill of materials including instruments (specifying tag, manufacturer, model, basic size or connection, basic materials, design pressure/temperature, calibration, special notes)
- Equipment/Piping layout
- Equipment data sheets (where applicable) for vessels, pumps, heat exchangers
- Fabrication drawings for vessels, and heat exchangers

4.2 Final Documentation

Final documentation (2 sets) as follows:
- Final versions of all above review documents (equipment/piping layout will not be as-built)
- designer notes
- vendor manuals

The following documentation is excluded:

- 3-dimensional routing of tubing
- any isometric drawings of piping and tubing
- operating procedures

5. Warranty

Zeton shall warrant the product to be free from defect in its workmanship of manufacture for a period under normal use of twelve (12) months from date of shipment. This constitutes Zeton's sole warranty for the product.

The warranty on materials and workmanship as to any apparatus, equipment or instrument incorporated in the product which is not manufactured by Zeton, will be the sole responsibility of the manufacturer thereof. Zeton will use its best efforts to transfer the benefits of such warranties to the buyer and to enforce the terms of the warranty on behalf of the buyer.

6. Factory Testing

Zeton will perform factory testing of the unit at its facility in Burlington, Ontario in the presence of the customer's personnel. The factory testing will be limited since the control system is not part of Zeton's scope of supply.

The skid will undergo the following tests at Zeton's facility prior to shipping. The client's personnel or representatives will be informed in advance of the tests should they choose to be present. No allowance in schedule or price has been made to allow for delays in these tests to meet the clients requirements to witness these tests.

- Completeness: mechanical and electrical
- Process piping and tubing will be hydrostatically or pneumatically tested in accordance with ANSI B31.3 pressure piping code.
- Wiring Continuity testing

7. **Payment Terms:**

The quoted prices are conditional upon the payment of the following progress payments made for project milestones:

1. 10% payment due upon placement of order.
2. 20% payment due upon completion of design approval documents.
3. 30% payment due upon completion by Zeton of issuing of purchase orders for major equipment (vessels, heat exchangers, and pumps).
4. 30% payment due upon completion of manufacturing of the pilot plant at Zeton's facility.
5. 10% payment due upon delivery of the pilot plant to the customer's facility.

Invoices will be submitted for each of the above milestones. Invoices are payable within thirty (30) days after the date thereof.

8. **Hazop Meeting**

Hazop for the pilot plant is to be done by the client. No allowance has been made in the quoted price for Zeton personnel to attend the Hazop. If this is required, labour costs on an hourly basis (rates shown in 2. above) plus travel and living expenses will be invoiced to the client separately.

9. **Validity**

The quoted price is fixed for sixty (60) days from the date of this quotation.

ALSO SEE ATTACHED ZETON INC. GENERAL TERMS AND CONDITIONS OF SALE.

100 KG PER DAY SSR UNIT

SCOPE OF WORK - TECHNICAL SECTION

1. Scope of Work

The quotation is for the SSR Unit based upon the following:

- P&ID 55-003-SSR 2R PF-001.4 Rev D
- Exchanger Design Cases, Rev 5
- Design Temperature Materials, Rev 5
- Reforming Air Pressure Drop, Rev 3
- Regeneration Air Pressure Drop, Rev 3
- Steam NG Pressure Drop, Rev 1
- Zeton's attached Scope of Work and specifications
- Chevron specifications PVM-EG-4748-B AND EXH-EG-4764

The pressure drop calculations are based upon best estimates. If upon detailed design, the pressure drop is higher than estimated; the plant will have to be run at lower rates to ensure that the pressures remain within the maximums allowed by the piping/flanges/equipment/valves/instrumentation as specified.

All equipment, instruments and valves shown on the P&ID are included in Zeton's scope of supply. The Air Compressor C-1, and the VFDs SC-1 and SC-2 will not be mounted on the skid. They will be shipped loose to site.

1.1 Process Simulation

Upon award of the contract, it is highly advisable that the client provide detailed simulations to confirm the physical properties, and finalize the thermal expansion design case(s) for the exchangers. The physical properties used for reformate by the exchanger manufacturer differed significantly from those on the data sheets, and also from those supplied by other manufacturers. The CUSTOMER is solely responsible for determining the thermal expansion design cases for the heat exchangers. Any changes in equipment sizing resulting from the process simulations will be at additional cost.

1.2 Codes and Specifications

The plant will be designed based on the following applicable design codes:

- ASME, Sect VIII, Div 1
- ANSI B31.3
- NEC

The plant will be fabricated in accordance with Zeton's standard pipe specifications, and Zeton's standard instrument installation details.

1.3 Reactor Design

There are a number of concerns with the reactor design (see clarification section below), including the lack of a mechanical or thermal design guarantee from the refractory lining supplier, RHI. It is highly advisable that Zeton, Chevron's experts, RHI, and possibly outside consultants hired by Chevron meet at the start of the project to address the concerns. Zeton has not made any allowance in the price for hiring outside refractory lining consultants. Any changes to the reactor price as a result of changes to the refractory material or reactor design will be at additional cost.

1.4 Clarifications to Scope of Work

This section clarifies Zeton's proposed scope of work for the skid mounted plant, and states assumptions which are made in preparing the quotation. The clarifications are based on Zeton's experience in the design and fabrication of skid mounted plants with similar requirements at a similar scale. Note that alterations in these assumptions used in defining Zeton's scope of work will have an effect on both price and delivery schedule.

1.4.1 Metallurgy

- The CUSTOMER has specified and/or approved materials of construction for the process, and hence the CUSTOMER is solely responsible for the suitability of these materials for the services. Any changes to the metallurgy will be at additional cost.

1.4.2 Reactor

- The quotation is based upon refractory lining from RHI Canada Inc, with Plivaform board as the coldface insulation, and Comprit 94 CD as the hotface insulation. RHI does not provide a mechanical or thermal guarantee for the design. They only guarantee is that the work will be free from installation defects. Zeton cannot assume any guarantees beyond that provided by RHI.
- RHI has based the thermal calculation for the Reactor refractory lining upon no hydrogen leaking through the Comprit 94 CD. As hydrogen has a much higher thermal conductivity than air and Plivaform board is porous, hydrogen leakage through will increase the thermal conductivity of the Plivaform board significantly (by a factor of 8 per Thermal Ceramics, another refractory lining supplier). Thermal Ceramics was very skeptical of RHI's assumption that the coldface insulation will be free of hydrogen. Zeton was also very skeptical. The heatloss and metal wall temperature will be much higher if the pores of the Plivaform board are filled with hydrogen.
- As the coldface insulation is porous and the pressure drop through the bed is high, cracks in the hotface insulation will result in significant bypassing of hot gas around the bed through the coldface insulation. This will likely result in the metal wall exceeding the design temperature of the vessel, and heatloss increasing significantly.
- The reactor refractory lining design detail for flanges needs to be reviewed to ensure that the flange temperatures remain under the design temperature, and heatloss is minimized (expecially for the internal refractory to external insulation transition pieces).

- The actual number of spare gaskets that the CUSTOMER will receive is one or two less than that indicated on the specification sheet, because some gaskets will be used up during testing.
- Specific Chevron pressure vessel specifications for carbon steel have not been provided, and therefore, have not been included in the price of the reactor.

1.4.3 Exchangers

- The customer is solely responsible for determining the thermal expansion design cases for the exchangers.
- One of the exchanger suppliers did not quote because they insisted that ASME VIII, Div 1 required that the exchanger tubes had to be designed based for external pressure whether or not that situation could occur or not. ASME VIII, Div 1 limits the temperature for 304H external pressure design to 1200F. For HX-1, the gas travels through the tubeside, through the reactor, and then through the shellside. However, it is possible that during the switch from regeneration to reforming that the tubes will be above 1200F and under external differential pressure. If this situation could occur, AV-1612 would have to be moved to the shellside inlet of HX-1. The cost for this potential change has not been included in the quotation.
- A differential pressure transmitter has been added to detect higher pressures on the shellside or HX-2 than the tubeside. The control system must be interlocked to shutdown the plant if such as situation occurs. This will limit the reactor operating pressures during reforming, especially during turndown. Similar to HX-1, AV-1610 may have to be moved to the shellside inlet of HX-2, and this cost has not been included in the quotation.
- Chevron specifications PVM-EG-4748-B AND EXH-EG-4764 have been provided to the exchanger fabricator
- HX-1 and HX-2 consists of multiple shells, supplied as an assembled skid. The exchanger manufacturer may use expansion joints to handle the thermal expansion of the interconnecting piping between shells.

1.4.4 Plant Location

- The design is based upon a temperate outdoor location (such as Houston, Texas). Winterization (electric or steam tracing) is not included in the quotation.

1.4.5 Instruments

- Type N thermocouples will be used throughout the plant. No RTD's have been specified.
- Unless a thermowell is shown on the P&ID, it has not been included. The thermowells on the reactor will be flanged. All other thermowells will be socketwelded.
- Skin mounted thermocouples will be used (mostly on tubing where direct insertion is impractical) where shown on the P&ID.
- Temperature transmitters will be Class 1, Div 2 non-incendive mounted in a Nema 4 electrical box. Heads on thermowell assemblies will not be explosion proof.

- No diaphragm seals and capillaries have been used in this plant for pressure measurement. All instruments are wetted directly by the process fluid. For high temperature pressure measurement, impulse lines will be uninsulated to keep the instrument cold. Uninsulated pigtails will be used where required to prevent reflux condensing from heating the pressure instrumentation. Impulse legs will be 316SS tubing with Swagelok fittings.
- Manifold are not included for any differential pressure transmitters.
- Local indication has not been included for any instrumentation.
- FE-6301 includes pressure and temperature compensation to obtain mass flow of the air.
- FTC-5601, 5602, 5603 are non-explosion proof and will be installed into a Z-purged Nema 4 enclosure to meet Class 1, Div 2, Grp B, C & D hazardous area location.
- The three way tubing control valve TV-1610B does not include a positioner. Positioners have been included for all other control valves.
- Independent airsets and filters will not be used for each control valve.
- Actuated ball valves have been specified based upon an air pressure of 80 psig minimum, 120 psig maximum. Regulation to this pressure is by Chevron
- The thermal mass flow controllers FTC-5601, 5602, and 5603 has been based upon an inlet pressure of 70 psig. Chevron is responsible for regulations of the natural gas pressure to meet these requirements.

1.4.6 Valves

- Only valves shown on the P&ID's will be provided.

1.4.7 Piping / Tubing

- Process piping material will be as per the P&ID.
- Copper/Brass tubing and brass Swagelok fittings or Galvanized pipe and 150# MI fittings will be used for instrument air headers. Branches will be connected to its users via polyethylene tubing and push-lock type fittings (i.e. Legris, MetalWorks, etc.).
- Except for possibly the interconnecting piping between the multiple shells of HX-1 and HX-2, no expansion joints have been included in the design.
- Some allowance has been made to minimize the length of piping between equipment and thus the associated heatloss. However, the lengths will not be optimized beyond what is reasonable.

1.4.8 Insulation

- Pipe and vessels will be insulted as per the thicknesses shown on the P&ID.
- Insulation of pipe and vessels is included in the scope. However, flanges and tubing connections will not be insulated. This is completed by the client on site after final pressure testing. Mineral wool will be used for temperatures below 600C and Superwool will be used above 600C. All insulated lines will be aluminum clad.

1.4.9 Electrical

- Lighting is not included in the price.
- All AC devices will be wired using Armor cables via cable tray.
- All instruments will be wired using PLTC cables to a Nema 4 junction box via cable trays. Connections from the cable tray to the instrument will be with flexible conduit
- The price does not include installation cables.
- Isolation transformers, RFI filters, or line and load reactors are not included in the scope.

1.4.10 Safety Relief

- Pressure safety valve and rupture disk sizing will be performed by Zeton, based only on the cases indicated by the customer in the Relief Contingency table (to be filled out during detailed design). If is advisable that the Relief Contingency table be filled out during the Hazop.
- Changes in the relief design cases after detailed sizing has been started will be at additional cost.
- The pricing is based upon a 2" rupture disk for PSE-1601, with two spare disks. Increase in size as result of detailed relief sizing will be at additional cost.
- PSE-1601 must be uninsulated to ensure that the pressure is below **600C** during operation.
- RLF-4601 will be a proportional non-ASME tubing relief valve.

1.4.11 Structural Design

- Structural design will be based upon 100 lb/ft2 live loading, and environmental (wind, earthquake) conditions for the area of construction.

1.4.12 Spare Parts

- Except for spare full body flange gaskets as shown on the Reactor specification sheet, and two spare rupture disks, spare parts have not been included in the scope of supply.

1.5 Skid Mounted Construction

The SSR Unit will be skid mounted. There will be three skids, one vertical and two horizontal. The vertical skid will have a footprint of about 12 ft x 12 ft. The two horizontal skids will have a footprint of about 12 ft x 30-40 ft each. The skids will be constructed from carbon steel HSS members and painted with acid resistant paint, with galvanized floor grating. All process, vent and utility piping and tubing will be installed to bulkheads at the edge of the skid. All wiring and cable will be installed and terminated in the Nema 4 rated enclosure on the skid.

Two ladders will be provided for the vertical skid, to allow two points of egress. Handrails will be provided at the top level of the vertical skid. No allowance has been made for handrail, grating, or ladders for access to the top of the two horizontal skids.

2 Electrical Classification / Scope of Supply

The SSR unit will be designed in accordance with the National Electrical Code, NEC, for Class 1, Div. 2, Group B, C, & D. As the Fired Preheater/Boiler/Superheater, the Reactor, and the surface temperature of externally insulated piping operates above the autoignition temperature, these will be exempt from the hazardous area requirements, as recommended in NFPA 497.

3 Control System

The control system (hardware, software, and configuration) will be done by Chevron, and has not been included in the scope of supply.

4 Site Installation

A very partial list of the client's responsibility for site installation includes the following:

- Site preparation/development
- Set-up of the process skid in place
- Leveling and anchoring of the skids
- Certificates, permits or licenses required for the installation and operation
- Connections of utilities, vent lines, process and sample lines to skid edge connection points
- Installation and wiring between the skids and the control room and MCC cabinets
- Leak testing, as required
- Electrical continuity testing, as required
- Commissioning and startup

Zeton personnel are available to supervise and assist in the above tasks as required.

5 Quality Assurance

The plant will be designed and fabricated in accordance with Zeton's registered ISO 9001:2000 Quality Assurance program. A copy of Zeton's ISO certification and a summary of our Quality Procedures Manual is available upon request.

6 Standard Safety Features

The people at Zeton offer over seventeen years of proven excellence in the design of safe pilot plants. Zeton has designed and built pilot plants operating with hazardous gases such as H2 and CO at pressures up to 5000 psig and temperatures to 1500°C. From design to delivery, each module is carefully evaluated to guarantee safety and functionality. All potential operating hazards are considered during the design, construction and commissioning phases of a project. Only proven equipment and control techniques are used in the design of Zeton's plants. Upon delivery to Zeton, each piece of equipment to be installed in a unit is subjected to and must pass a detailed inspection and testing. If the equipment does not pass this preliminary inspection, it will be returned to the manufacturer and replaced with equipment that passes the testing requirements.

After the unit has been assembled at Zeton it undergoes either a hydrostatic or pneumatic pressure test, depending on what is appropriate for the type of pilot plant. All critical temperature control loops and high temperature heat trace circuits have a separate thermocouple and temperature safety switch. All process modules are designed to fail in a safe mode, in the event of a power failure, or failure of air supply to pneumatic actuators. All high pressure lines are equipped with relief valves, and pressure vessels are equipped with rupture disks and/or relief valves as a final level of overpressure protection. All pressure vessels are designed and fabricated in accordance with ASME Section VIII, and are hydrostatically tested at the vessel fabrication shop. All piping and tubing is designed and fabricated in accordance with ANSI B31.3.

Typical safety features included into the design to ensure safe operation are:

a) The "fail-safe" philosophy has been incorporated into the design of the pilot plant. In the event of power failure or loss of instrument air, each remote air operated valve, electrical solenoid valve, and pneumatic control valve, will fail into its "safe" position.

b) Three levels of safety are employed for all critical parameters (temperature, pressure). The first level consists of high and low alarms on all computer monitored transmitters and control loops which are all user configurable. A second level of high-high and low-low alarms, are predominantly mandated by the equipment safety limitations and are configured by Zeton. Individual alarm actions are also preprogrammed to cause shutdown of a particular component (for example gas feed, pump, heater) or of the entire system if an alarm value is exceeded. These steps automatically return the system to a safe condition. In addition to the two levels of digital alarm actions, a third level consisting of independent safety switches or mechanical back ups (pressure relief devices) are provided.

c) Emergency Shutdown stop switch to bring the system automatically to a safe mode.

7. Zeton Qualifications

Zeton Inc. is a private company specializing in the custom design and manufacturing of automated, modular processing systems. These systems include laboratory units, pilot plants, demonstration plants, and modular commercial production plants. The corporation's personnel have gained considerable experience from the design and construction of over six hundred pilot, demonstration and modular commercial plants. This includes specialized experience in the design of reactors and control systems, knowledge of reliable suppliers of the equipment and instrumentation and control elements required, as well as experience in the manufacturing, testing, debugging and commissioning of pilot plants.

Zeton's staff consists of chemical engineers, mechanical engineers, electrical and control system engineers, as well as electrical and mechanical technicians. All personnel are experienced in their particular area of contribution towards Zeton's projects and are capable of effective execution of pilot plant design, construction, testing, installation and commissioning. In addition, the project engineers are experienced in providing efficient project management.

Zeton takes full responsibility for detailed engineering design, instrumentation and control system design, procurement, construction, installation, start-up and operator training. Most of the systems we have built are automated using computer based control, PLC's or DCS's.

Zeton uses a modular design and construction approach for its pilot plants. This gives our systems the flexibility required for process changes and development. Modules can easily be changed, replaced or added as the needs of the unit develops. Modular construction also reduces the project cost and schedule, and the installation and start-up period for the plant.